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CONTINUOUS AND DISCRETE DESCRIBING FUNCTION
ANALYSIS OF THE IPS SYSTEM (Systems Research
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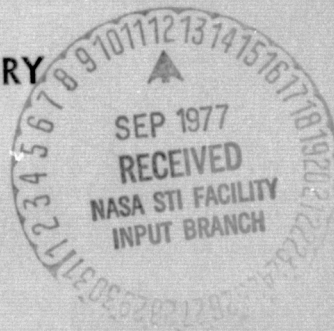
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RESEARCH STUDY ON STABILIZATION AND CONTROL
MODERN SAMPLED-DATA CONTROL THEORY

SYSTEMS RESEARCH LABORATORY

P.O. BOX 2277, STATION A
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PREPARED FOR GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

BIMONTHLY REPORT

DIGITAL CONTROLLER DESIGN

subtitle:

CONTINUOUS AND DISCRETE
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OF THE IPS SYSTEM

August 1, 1977

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VI. DIGITAL COMPUTER SIMULATION OF THE DIGITAL IPS SYSTEM WITH WIRE-CABLE AND FLEX-PIVOT NONLINEARITY

In this chapter the digital IPS with wire-cable and flex-pivot nonlinearity is simulated on the digital computer. The main objectives of these simulations are to determine the effects of varying the sampling period T on the system stability, and to determine a range of "optimal" values of the parameters of the digital controller, K_p , K_i and K_r .

The listing of the computer program is shown in Table 6-1. The parameters of the Dahl model for the flex-pivot nonlinearity are:

$$\gamma = 92444$$

$$T_{FPO} = 2.25 \times 10^{-3} \text{ N-M}$$

For the wire-cable nonlinearity, two ranges of values were used for K_{WT} and H_{WT} :

$$\begin{array}{ll} K_{WT} = 100 & K_{WT} = 0.25 \\ H_{WT} = 1 & H_{WT} = 0.01 \end{array}$$

The nominal values of the digital controller parameters are:

$$\begin{array}{l} K_p = 70000 \\ K_i = 1.1 \times 10^5 \\ K_r = 19700 \end{array}$$

6.1 Nominal Controller Parameters With Variable Sampling Periods

The first set of simulations involves the study of the effects of various sampling rates. Figures 6-1 through 6-5 show the time responses of θ_i due to an initial condition of $\theta_i(0) = 10^{-7}$, for the nominal values of K_p , K_i and K_r ; $K_{WT} = 0.25$ and $H_{WT} = 0.01$, and T varies from 0.005 sec

```

PROGRAM IPSSIM(INPUT,IPSD2,TAPE6-IPSD2,OUTPUT)
IMPLICIT REAL(N)
COMMON S10SS,AKT,AKP,AKR,AK45,AK46,S10RG,D77,M77,AK77,HZC,HXC
1,M1,MR,MS,NN,M41,M11,M31,KCZ,M42,RCX,M32,M22,BUS,
2AKUS,M31,M33,M37,MU,MV,B66,M66,MP,MR,AK66,M67,M62,
3HWT,AKW1,K0,G1,SLAST,TFPO,S10TM,II
COMMON/RRGSIN/IRIT(9),HOLDAT(11)
EXTERNAL FCTY,OUTP
DIMENSION Y(11),DERY(11),AUX(8,11)
C NONLINEARITY CONSTANTS
AKWT-1.0E2*HWT-1.E0
GAMA-9.2444E4*TFPO-2.25E-3
G1-GAMA*TFPO.
C INITIAL CONDITIONS
Y(3)-1.E-7*SLAST-Y(3)
II-0
A-2.E0*G1*SLAST
A1-1.E0/A
RO--1.E0*(-A1+SQRT(A1**2+1.E0))
C INITIALIZE STATES
NDIM-11
DO 1 I=1,NDIM
IF(I.EQ.3)GO TO 1
Y(I)-0.E0
1 CONTINUE
C SET SYSTEM CONSTANTS
C MASS CONSTANTS ARE;
M11-9.12E4*M13--2.26E2*M14-2.27E3
M22-M11*M23-1.66E4*M24-3.92E3
M31-M13*M32-M23*M33-7.06E6*M34-2.67E4
M41-M14*M42-M24*M43-M34*M44-1.03E4
M51--1.E0*M53-9.29E-1*M55-1.E0*M57--1.13E-3
M62--1.E0*M63--4.72E0*M66-M55*M67-1.37E-3
M77-M55
C SET DAMPING CONSTANTS
D43-1.97E4*D44-D43*D47--76.4E0
D55-44.E0*D66-D55*D77-.115E0
C SET STIFFNESS CONSTANTS
AK43-7.E4*AK44-AK43*AK45--2.23E6
AK46--3.87E6*AK47--2.72E2*AK55-9.66E2
AK66-9.66E2*AK77-1.32E2
C SET FID CONSTANTS
AKR-D44*S10RG-D47/AKR
AKP-AK44*S10SS-AK47/AKP
Q43-1.1E0*AK1-Q43*Q44-Q43
Q47--4.27E2*S10TM-S10SS
C SET DISTANCES FROM CENTER OF MASSES & CENTER OF GRAVITIES
C SET TO ONE IF THE CREW MOTION IS NOT INCLUDED IN THE MODEL
HZC-1.E0*HXC-1.E0
RCX-1.E0*RCZ-1.E0
C DEFINE AGREGATE MASS ELEMENTS
M1-M34-M31*M14/M11-M32*M24/M22
MR-M43-M13*M41/M11-M42*M23/M22
MS-M53-M13*M31/M11-M32*M23/M22
NN-M44-M14*M41/M11-M42*M24/M22
MU-M53-M31*M13/M11
MV--M51*M14/M11
MP--M62*M23/M22+M63
MR--M62*M24/M22
C SET ERROR WEIGHTING FACTORS
DO 5 I=1,NDIM
5 DERY(I)-1.E0/11.E0
C SET RRGS CONTROL PARAMETERS
PRMT(1)-0.E0
PRMT(2)-0.0E0
PRMT(3)-1.E-3
PRMT(4)-1.E-14
PRMT(5)-0.E0
PRMT(7)-PRMT(1)
PRMT(8)-1.0E-1
PRMT(6)-1.E-1
PRMT(9)-PRMT(1)
CALL RRGS(PRMT,Y,DERY,NDIM,IHLF,FCTY,OUTP,AUX)
STOP
END

```

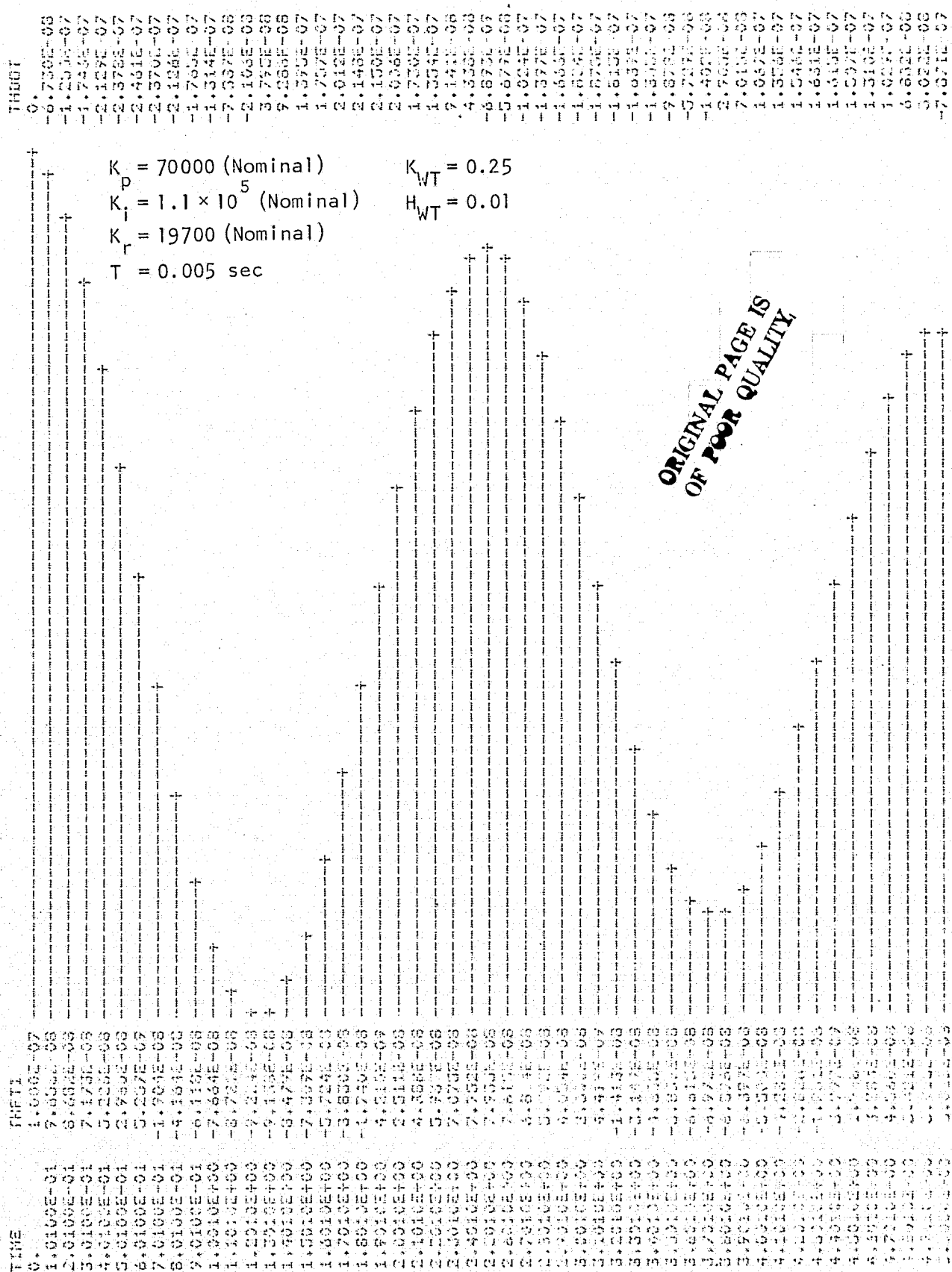
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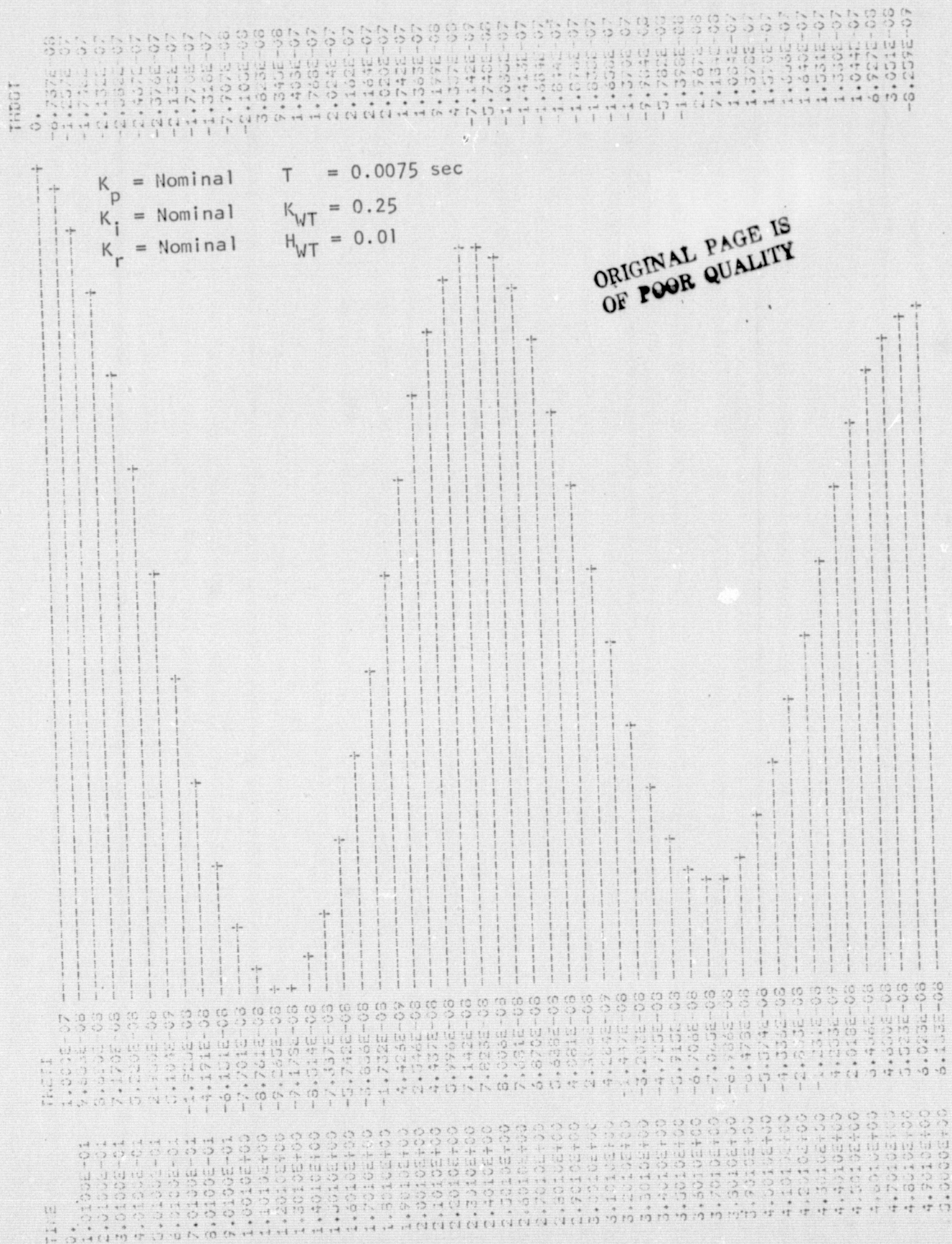
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SUBROUTINE OUTP(TIME,Y,DERY,INLP,NDIM,PRMT)
  DIMENSION Y(NDIM),DERY(NDIM),PRMT(9)
  IF((TIME.GE.PRMT(7)).GO TO 1
  RETURN
1  PRMT(7)=PRMT(7)+PRMT(6)
  WRITE(6,10)INLP,TIME,Y(3),Y(8)
10  FORMAT(14,2X,1PE10.4,1P2E11.3)
  RETURN
END
SUBROUTINE FCTY(TIME,STATE,STDOT,KEEP,NDIM)
  IMPLICIT REAL(M)
  COMMON SI093,AK1,AKP,AKR,AK40,AK46,SI0R0,D77,M77,AK77,HZC
1, HXC,M1,MK,MS,MN,M41,M11,M31,RCZ,M42,RCX,M32,M22,D55
2, AK05,M51,M55,M57,M5,M5,M56,M66,M6,M6,AK66,M67,M62,HWT,
3 AKWT,R0,G1,SLAST,TFF0,SI0TM,II
  COMMON/KK09IN/PRMT(9),HOLDAT(11)
C THIS SUBROUTINE ONLY UPDATES THE DERIVATIVE OF THE STATE VECTOR.
C THE UPDATE DEPENDS ON THE INPUTS, TIME, STATE, & KEEP.
  DIMENSION STATE(NDIM),STDOT(NDIM)
  FX(TIME)=0.E0
  FZ(TIME)=0.E0
C 10- FORMAT(16,1PE10.4,1P2E11.3)
C MODEL THE WIRE NONLINEARITY
  SGNEDT=1.E0
  IF(STATE(8).LT.0.E0)SGNEDT=-1.E0
  TWC=SGNEDT*HWT*AKWT*STATE(3)
C MODEL FOR THE DAHL NONLINEARITY (F-2)
  IF((TIME.GT.0.E0).GO TO 1
  GO TO 2
1  II=1
2  R1=R0-SGNEDT
  TFF=(SGNEDT+R1/(1.E0-G1*(STATE(3)-SLAST)*R1))*TFF0
  IF(TFF.GT.TFF0)TFF=TFF0
  IF(TFF.LT.-TFF0)TFF=-TFF0
  IF(II.EQ.0)GO TO 3
  R0=TFF/TFF0
  II=0
  SLAST=STATE(3)
  GO TO 2
3  TFF=3.E0*TFF
  ENN=TFF+TWC
  STDOT(1)=STATE(6)
  STDOT(2)=STATE(7)
  STDOT(3)=STATE(8)
  STDOT(4)=STATE(9)
  STDOT(5)=STATE(10)
C IF A NEW INTEGRATION & A NEW SAMPLE TIME THEN UPDATE THE CONTROL.
  IF((TIME.GE.PRMT(7)).AND.(KEEP.EQ.0))GO TO 4
  GO TO 5
4  PRMT(7)=PRMT(7)+PRMT(6)
  HOLDAT(1)=STATE(2)+STATE(3)+SI093*STATE(1)
  HOLDAT(2)=AK1*STATE(11)+AKP*HOLDAT(1)+AK40*STATE(4)+AK46*STATE(
15)+AKR*(STATE(7)+STATE(8)+SI0R0*STATE(6))
5  STDOT(11)=HOLDAT(1)
  TCM=ENN+HOLDAT(2)
  STDOT(6)=-D77/M77*STATE(6)-AK77/M77*STATE(1)-SI0TM/M77*TCM
1+HZC/D77*FZ(TIME)+FX(TIME)*HXC/D77
  STDOT(7)=-1.E0/(1.E0-M1*MK/MS/MN)*(M1/MS/MN*TCM+(M1*M41/(MS*MN*
1M11)-(RCZ+M31/M11)/MS)*FX(TIME)+(M1*M42/(MS*MN*M11)+(RCX
1M32/M22)/MS)*FZ(TIME))
  STDOT(8)=-MK/MN*STDOT(7)-TCM/MN-M41/MN/M11*FX(TIME)-M42/MN/
1M11*FZ(TIME)
  STDOT(9)=-D55/M55*STATE(9)-AK55/M55*STATE(4)-M51/M11/M55*FX(
1TIME)-M57/M55*STDOT(6)-MU/M55*STDOT(7)-MV/M55*STDOT(8)
  STDOT(10)=-D66/M66*STATE(10)-AK66/M66*STATE(5)-M67/M66*STDOT(
16)-MP/M66*STDOT(7)-MR/M66*STDOT(8)-M62/M22/M66*FZ(TIME)
  KEEP=1
  RETURN
END

```

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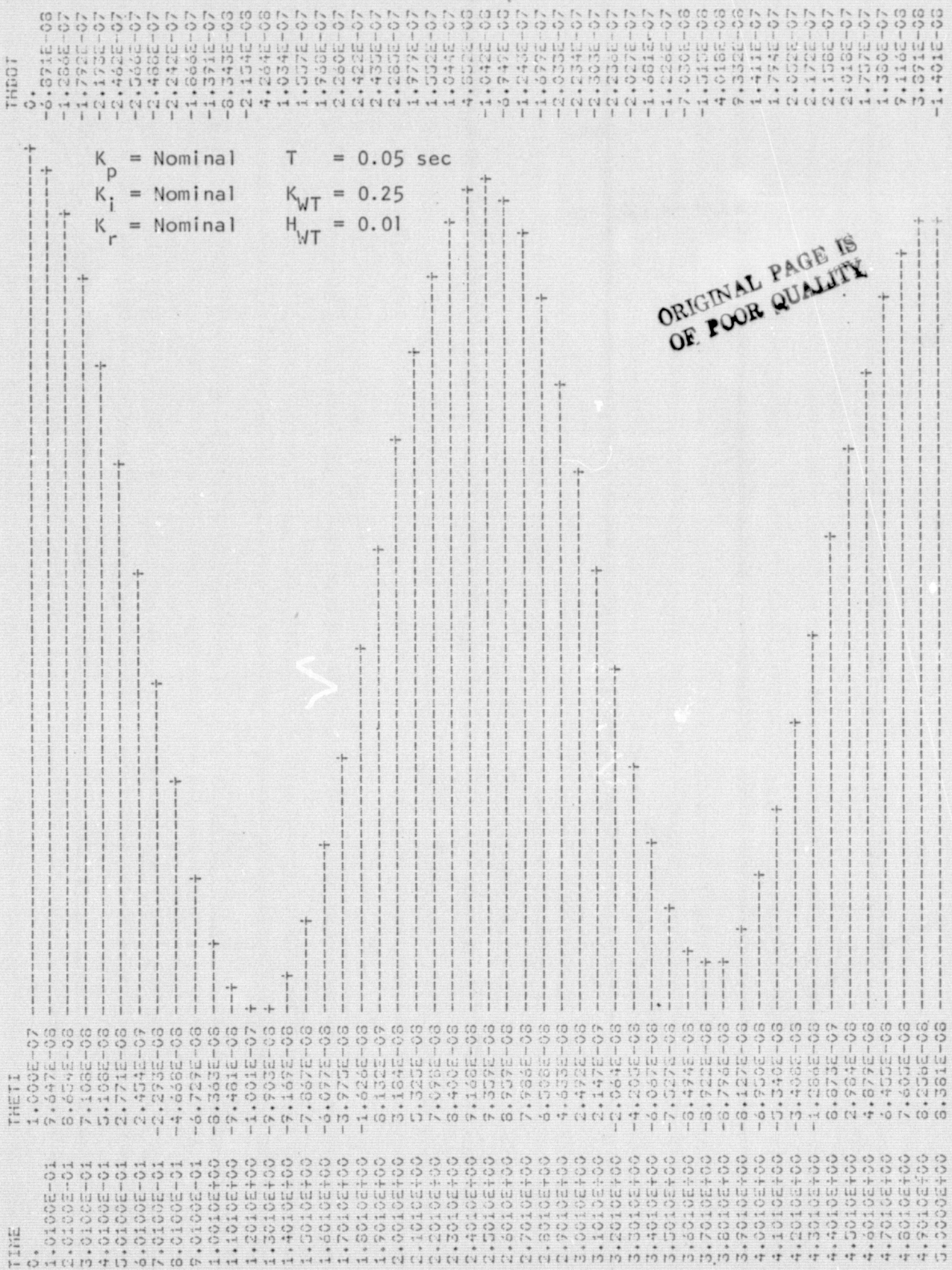


Figure 6-3.

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Item	Item	Item
9.	1.000E-07	1.000E-07
1.000E+00	7.23E-06	1.47E-07
1.000E+00	4.04E-06	1.00E-07
1.000E+00	2.79E-06	1.00E-07
1.000E+00	7.10E-06	1.00E-07
1.000E+00	1.70E-07	1.00E-07
1.000E+00	1.00E-07	1.00E-07
1.000E+00	4.75E-06	1.00E-07
1.000E+00	3.10E-06	1.00E-07
1.000E+00	1.04E-07	1.00E-07
1.000E+01	1.38E-07	1.00E-07
1.101E+01	1.23E-07	1.00E-07
1.200E+01	5.55E-06	1.00E-07
1.300E+01	3.06E-06	1.00E-07
1.400E+01	1.17E-07	1.00E-07
1.501E+01	1.00E-07	1.00E-07
1.600E+01	1.41E-07	1.00E-07
1.700E+01	6.47E-06	1.00E-07
1.801E+01	3.85E-06	1.00E-07
1.900E+01	1.37E-07	1.00E-07
2.001E+01	1.85E-07	1.00E-07
2.100E+01	1.63E-07	1.00E-07
2.200E+01	7.50E-06	1.00E-07
2.301E+01	4.41E-06	1.00E-07
2.400E+01	1.58E-07	1.00E-07
2.501E+01	2.13E-07	1.00E-07
2.600E+01	1.87E-07	1.00E-07
2.700E+01	8.72E-06	1.00E-07
2.800E+01	5.33E-06	1.00E-07
2.900E+01	1.82E-07	1.00E-07
3.000E+01	2.45E-07	1.00E-07
3.100E+01	2.17E-07	1.00E-07
3.200E+01	1.00E-07	1.00E-07
3.300E+01	6.06E-06	1.00E-07
3.401E+01	2.06E-07	1.00E-07
3.500E+01	2.81E-07	1.00E-07
3.600E+01	2.49E-07	1.00E-07
3.700E+01	1.16E-07	1.00E-07
3.800E+01	6.87E-06	1.00E-07
3.900E+01	2.38E-07	1.00E-07
4.000E+01	3.23E-07	1.00E-07
4.100E+01	2.87E-07	1.00E-07
4.200E+01	1.34E-07	1.00E-07
4.300E+01	7.73E-06	1.00E-07
4.401E+01	2.67E-07	1.00E-07
4.500E+01	3.70E-07	1.00E-07
4.600E+01	3.27E-07	1.00E-07
4.700E+01	1.55E-07	1.00E-07
4.800E+01	8.70E-06	1.00E-07
4.901E+01	3.07E-07	1.00E-07
5.000E+01	4.23E-07	1.00E-07
5.100E+01	3.78E-07	1.00E-07
5.200E+01	1.80E-07	1.00E-07
5.300E+01	9.80E-06	1.00E-07
5.401E+01	3.51E-07	1.00E-07
5.500E+01	4.83E-07	1.00E-07
5.600E+01	4.35E-07	1.00E-07
5.700E+01	2.09E-07	1.00E-07
5.800E+01	1.10E-07	1.00E-07
5.900E+01	4.05E-07	1.00E-07
6.000E+01	5.58E-07	1.00E-07
6.100E+01	5.01E-07	1.00E-07
6.200E+01	2.43E-07	1.00E-07
6.300E+01	1.23E-07	1.00E-07
6.400E+01	4.64E-07	1.00E-07
6.500E+01	6.41E-07	1.00E-07
6.600E+01	5.77E-07	1.00E-07
6.700E+01	2.82E-07	1.00E-07
6.800E+01	1.38E-07	1.00E-07
6.900E+01	5.31E-07	1.00E-07
7.000E+01	7.37E-07	1.00E-07
7.100E+01	6.66E-07	1.00E-07
7.200E+01	3.29E-07	1.00E-07
7.300E+01	1.55E-07	1.00E-07
7.400E+01	6.07E-07	1.00E-07
7.500E+01	3.48E-07	1.00E-07
7.600E+01	7.70E-07	1.00E-07
7.700E+01	3.83E-07	1.00E-07
7.800E+01	1.74E-07	1.00E-07
7.900E+01	6.97E-07	1.00E-07
8.000E+01	9.76E-07	1.00E-07
8.100E+01	8.87E-07	1.00E-07
8.200E+01	4.46E-07	1.00E-07
8.300E+01	1.95E-07	1.00E-07
8.400E+01	7.77E-07	1.00E-07
8.500E+01	1.12E-06	1.00E-07

K_p = Nominal

K_i = Nominal

K_r = Nominal

T = 0.1 sec

K_{WT} = 0.25

H_{WT} = 0.01

Figure 6-5.

to 0.1 sec. As shown in Fig. 6-1, when $T = 0.005$ sec, the sampling period is sufficiently small that the response of the digital system approaches that of the continuous-data system. As the sampling period increases, the decay time of the oscillation increases, and the system is marginally stable when $T = 0.075$ sec (Fig. 6-4). Figure 6-5 shows that when $T = 0.1$ sec, the response of θ_i diverges when time increases, and the system is unstable.

6.2 Effects of Varying K_{WT} and H_{WT}

It has been shown earlier in the study of the continuous-data IPS that the values of K_{WT} and H_{WT} do not affect the system performance substantially. Figures 6-6 and 6-7 are reruns of the cases in Figs. 6-4 and 6-5, respectively, except with $K_{WT} = 100$ and $H_{WT} = 1$. These figures show that varying the values of K_{WT} and H_{WT} by the wide margin did not change the responses of the system in any significant way.

6.3 Effects of Varying K_p

In this section, simulations were conducted with

$$K_r = \text{Nominal value}$$

$$K_i = \text{Nominal value}$$

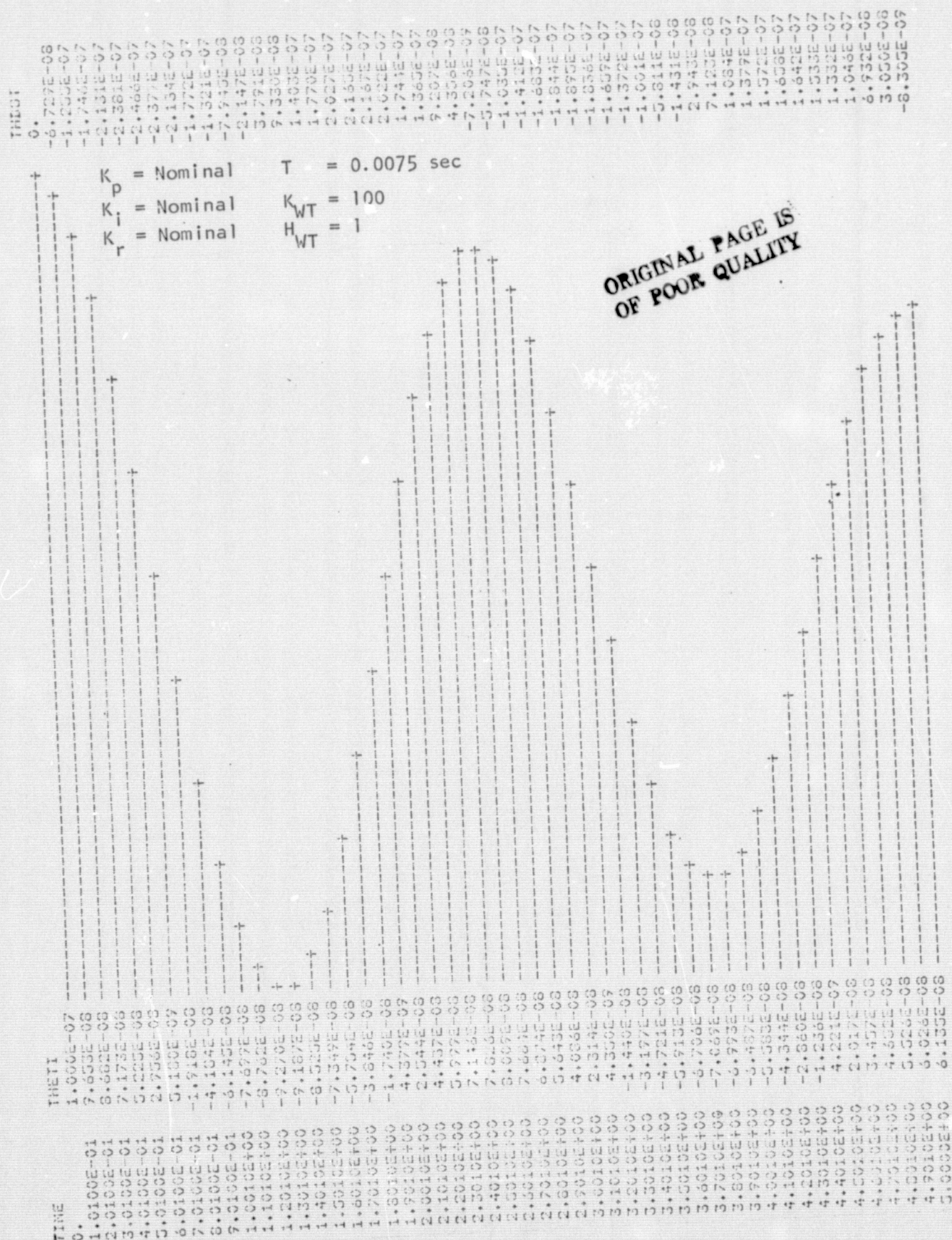
$$K_{WT} = 100$$

$$H_{WT} = 1$$

$$T = 0.1 \text{ sec}$$

and K_p is varied between 0.25 times to 5 times its nominal value.

Figures 6-8 through 6-13 show the simulation results for θ_i , due to an initial condition of $\theta_i(0) = 10^{-7}$. Figure 6-8 shows that when K_p is $1/4$ its nominal value, the system is unstable. As K_p is increased, the system becomes stable. However, when K_p is 5 times its nominal value, the



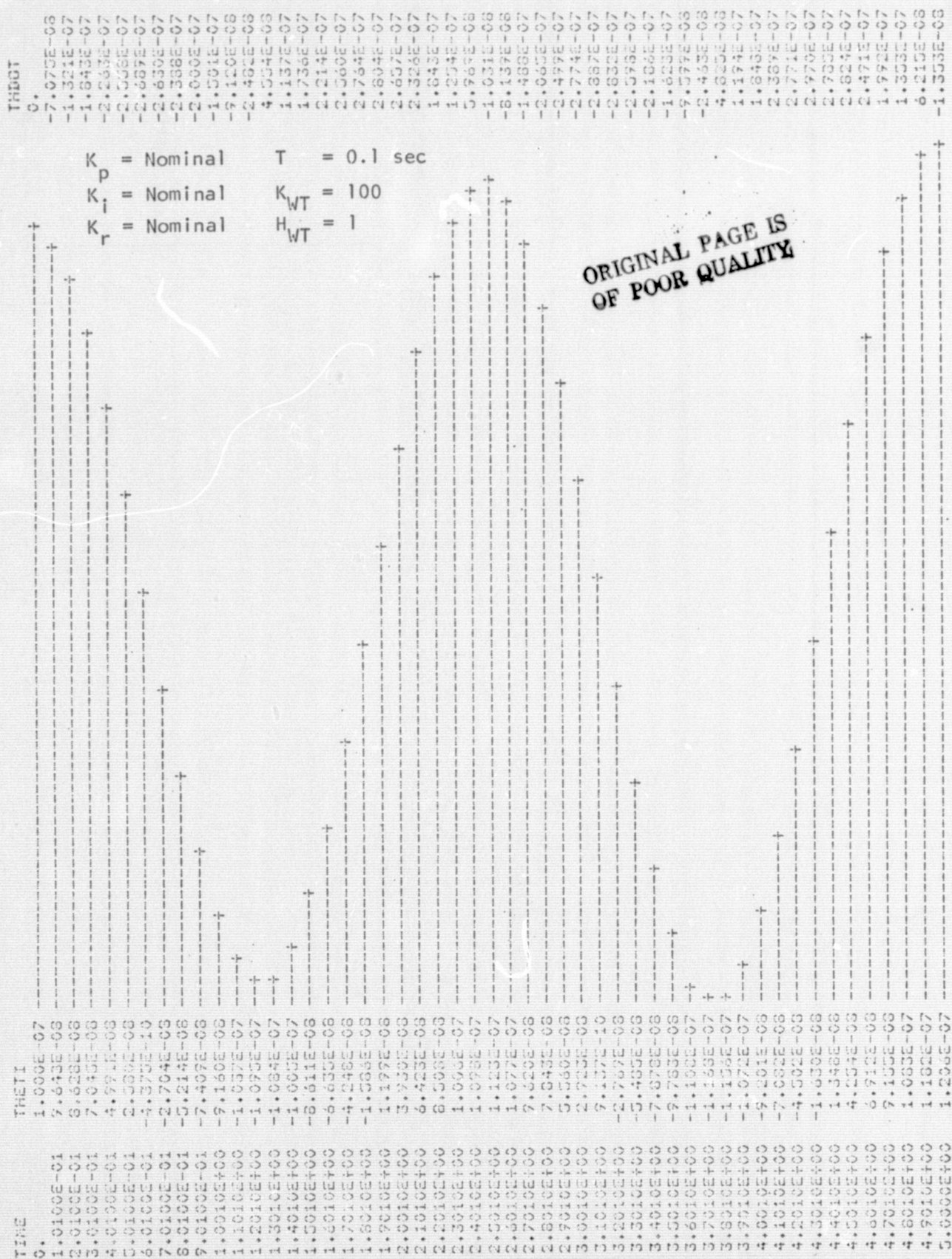


Figure 6-7.

TIME	THET	THDOT
0.	1.000E-07	0.
1.010E-01	9.911E-00	-1.761E-08
2.010E-01	9.814E-08	-4.179E-08
3.010E-01	9.650E-08	-7.116E-08
4.010E-01	8.173E-08	-1.044E-07
5.010E-01	6.952E-08	-1.397E-07
6.010E-01	5.378E-08	-1.751E-07
7.010E-01	3.431E-08	-2.082E-07
8.010E-01	1.234E-08	-2.372E-07
9.010E-01	-1.255E-08	-2.605E-07
1.0010E+00	-3.942E-08	-2.768E-07
1.1010E+00	-6.749E-08	-2.844E-07
1.2010E+00	-9.579E-08	-2.815E-07
1.3010E+00	-1.232E-07	-2.669E-07
1.4010E+00	-1.486E-07	-2.402E-07
1.5010E+00	-1.707E-07	-2.013E-07
1.6010E+00	-1.883E-07	-1.508E-07
1.7010E+00	-2.003E-07	-8.887E-08
1.8010E+00	-2.055E-07	-1.650E-08
1.9010E+00	-2.031E-07	6.459E-08
2.0010E+00	-1.923E-07	1.516E-07
2.1010E+00	-1.727E-07	2.414E-07
2.2010E+00	-1.441E-07	3.308E-07
2.3010E+00	-1.067E-07	4.164E-07
2.4010E+00	-6.111E-08	4.951E-07
2.5010E+00	-8.241E-09	5.621E-07
2.6010E+00	5.055E-08	6.135E-07
2.7010E+00	1.135E-07	6.455E-07
2.8010E+00	1.785E-07	6.551E-07
2.9010E+00	2.433E-07	6.399E-07
3.0010E+00	3.052E-07	5.777E-07
3.1010E+00	3.614E-07	5.269E-07
3.2010E+00	4.092E-07	4.273E-07
3.3010E+00	4.456E-07	3.001E-07
3.4010E+00	4.680E-07	1.476E-07
3.5010E+00	4.740E-07	-2.653E-08
3.6010E+00	4.618E-07	-2.173E-07
3.7010E+00	4.300E-07	-4.200E-07
3.8010E+00	3.776E-07	-6.279E-07
3.9010E+00	3.045E-07	-8.327E-07
4.0010E+00	2.116E-07	-1.026E-06
4.1010E+00	1.004E-07	-1.198E-06
4.2010E+00	-2.662E-08	-1.342E-06
4.3010E+00	-1.661E-07	-1.447E-06
4.4010E+00	-3.137E-07	-1.506E-06
4.5010E+00	-4.646E-07	-1.510E-06
4.6010E+00	-6.128E-07	-1.455E-06
4.7010E+00	-7.524E-07	-1.336E-06
4.8010E+00	-8.767E-07	-1.151E-06
4.9010E+00	-9.795E-07	-9.002E-07
5.0000E+00	-1.053E-06	-5.902E-07

 K_r = Nominal T = 0.1 sec K_i = Nominal K_{WT} = 100 K_p = $0.25 \times \text{Nominal}$ H_{WT} = 1ORIGINAL PAGE IS
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Figure 6-3.

LINE	THETA	THDOT
0.	1.000E-07	0.
1.	9.464E-08	-1.042E-07
2.	7.979E-08	-1.906E-07
3.	5.764E-08	-2.522E-07
4.	3.050E-08	-2.903E-07
5.	8.034E-10	-3.033E-07
6.	-2.876E-08	-2.879E-07
7.	-5.531E-08	-2.429E-07
8.	-7.617E-08	-1.742E-07
9.	-8.951E-08	-9.243E-08
1.	-9.453E-08	-8.043E-09
1.	-9.129E-08	7.297E-08
1.	-8.030E-08	1.467E-07
1.	-6.256E-08	2.080E-07
1.	-3.970E-08	2.489E-07
1.	-1.409E-08	2.632E-07
1.	1.161E-08	2.505E-07
1.	3.494E-08	2.160E-07
1.	5.406E-08	1.661E-07
1.	6.761E-08	1.048E-07
2.	7.458E-08	3.455E-08
2.	7.435E-08	-3.914E-08
2.	6.702E-08	-1.074E-07
2.	5.359E-08	-1.611E-07
2.	3.574E-08	-1.957E-07
2.	1.539E-08	-2.113E-07
2.	-5.677E-09	-2.098E-07
2.	-2.572E-08	-1.909E-07
2.	-4.298E-08	-1.541E-07
2.	-5.578E-08	-1.018E-07
3.	-6.399E-08	-4.098E-08
3.	-6.293E-08	1.968E-08
3.	-5.930E-08	7.412E-08
3.	-4.960E-08	1.198E-07
3.	-3.583E-08	1.553E-07
3.	-1.920E-08	1.773E-07
3.	-1.246E-09	1.815E-07
3.	1.616E-08	1.665E-07
3.	3.139E-08	1.357E-07
3.	4.235E-08	9.1509E-08
3.	5.005E-08	4.852E-08
4.	5.260E-08	1.313E-09
4.	5.031E-08	-4.724E-08
4.	4.335E-08	-9.165E-08
4.	3.249E-08	-1.257E-07
4.	1.896E-08	-1.488E-07
4.	4.274E-09	-1.403E-07
4.	-1.019E-08	-1.215E-07
4.	-2.328E-08	-9.268E-08
4.	-3.399E-08	-5.508E-08
5.	-4.131E-08	

K_r = Nominal
 K_i = Nominal
 K_p = $1.5 \times$ Nominal

T = 0.1 sec
 K_{WT} = 100
 H_{WT} = 1

Figure 6-9.

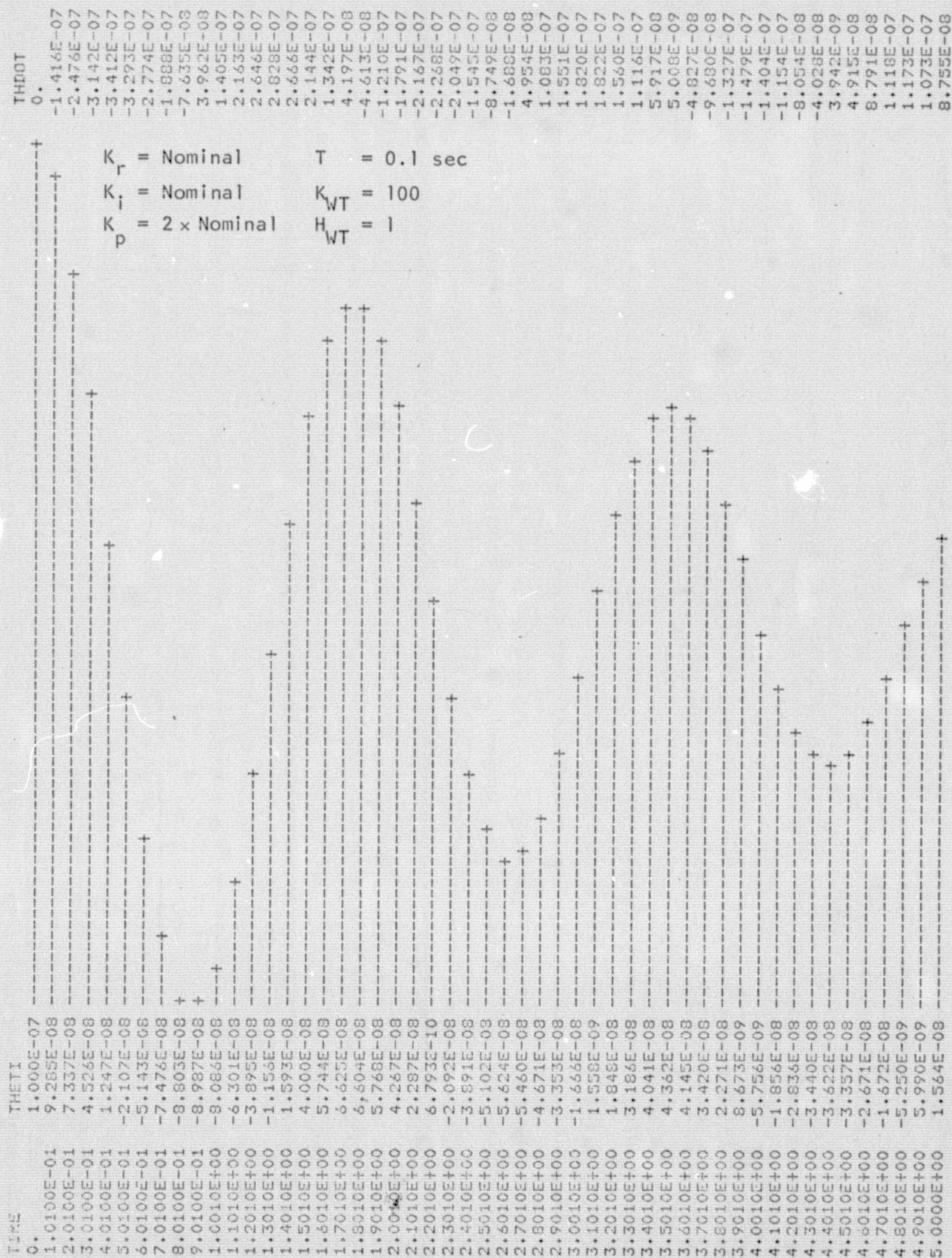


Figure 6-10.

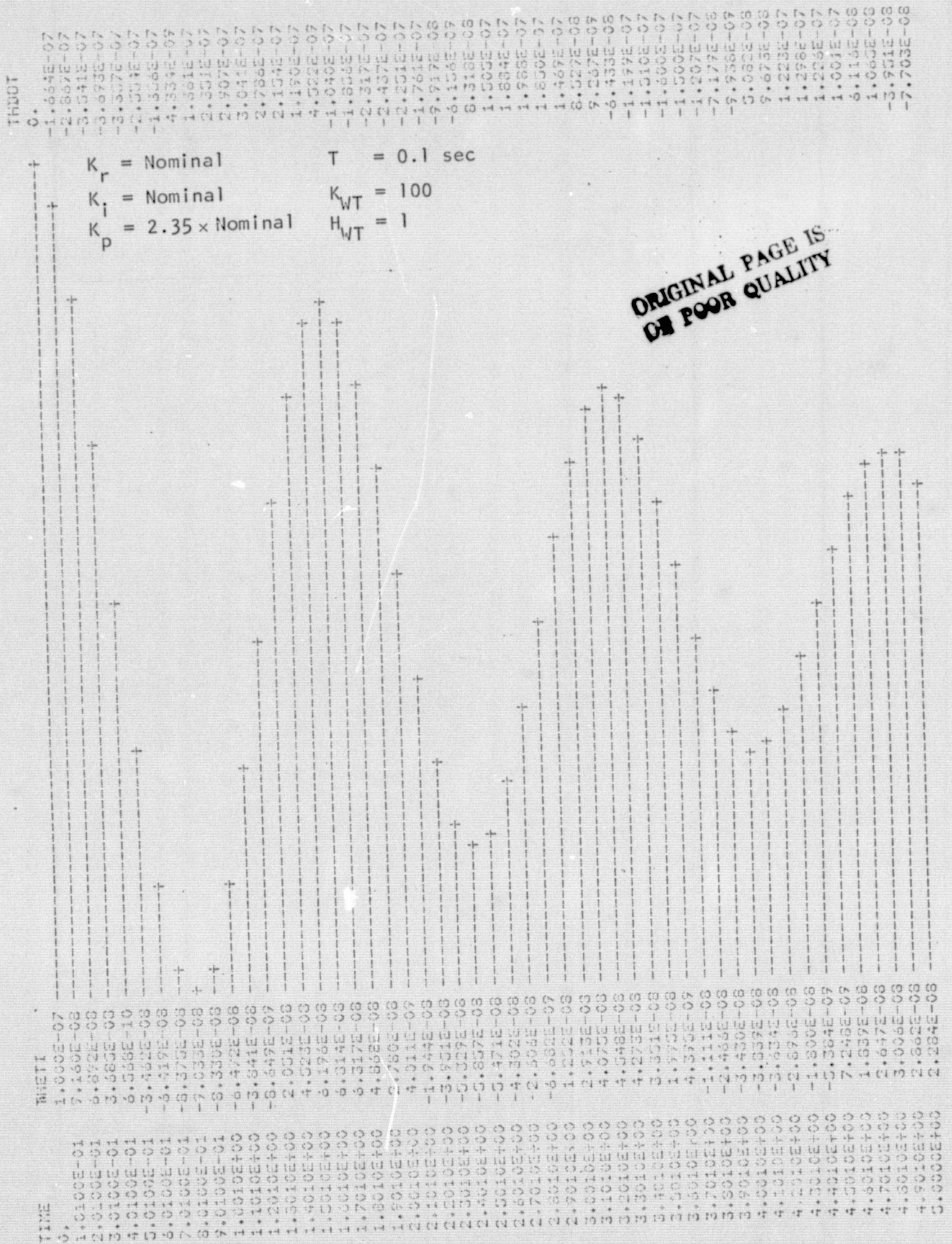


Figure 6-11.

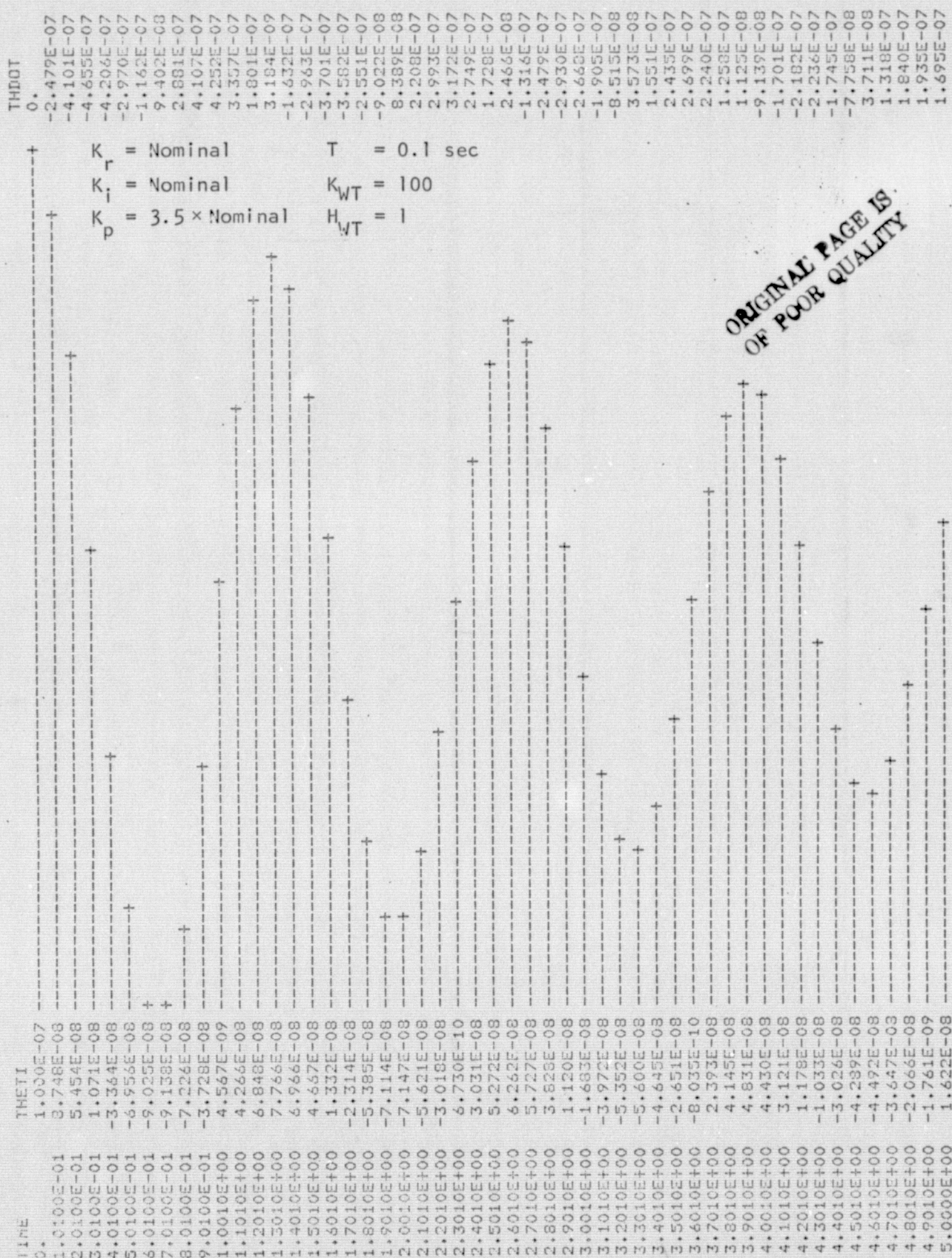


Figure 6-12.

LINE		THETI		THDOT	
0.	1.000E-07	1.000E-07	0.	0.	0.
1.	0.100E-01	8.212E-08	---	---	-3.541E-07
2.	0.100E-01	3.635E-08	---	---	-5.597E-07
3.	0.100E-01	-2.005E-08	---	---	-5.664E-07
4.	0.100E-01	-6.854E-08	---	---	-4.017E-07
5.	0.100E-01	-9.552E-08	+	+	-1.369E-07
6.	0.100E-01	-9.447E-08	+	+	1.584E-07
7.	0.100E-01	-6.552E-08	---	---	4.202E-07
8.	0.100E-01	-1.581E-08	---	---	5.731E-07
9.	0.100E-01	4.019E-08	---	---	5.452E-07
1.	0.101E+00	8.359E-08	---	---	3.207E-07
1.	1.010E+00	9.849E-08	---	---	-2.369E-08
1.	2.010E+00	7.982E-08	---	---	-3.491E-07
1.	3.010E+00	3.553E-08	---	---	-5.359E-07
1.	4.010E+00	-1.847E-08	---	---	-5.421E-07
1.	5.010E+00	-6.543E-08	---	---	-3.956E-07
1.	6.010E+00	-9.270E-08	---	---	-1.468E-07
1.	7.010E+00	-9.292E-08	---	---	1.450E-07
1.	8.010E+00	-6.481E-08	---	---	4.169E-07
1.	9.010E+00	-1.522E-08	---	---	5.737E-07
2.	0.010E+00	4.040E-08	---	---	5.367E-07
2.	1.010E+00	8.249E-08	---	---	3.033E-07
2.	2.010E+00	9.604E-08	---	---	-3.338E-08
2.	3.010E+00	7.748E-08	---	---	-3.375E-07
2.	4.010E+00	3.505E-08	---	---	-5.099E-07
2.	5.010E+00	-1.667E-08	---	---	-5.229E-07
2.	6.010E+00	-6.269E-08	---	---	-3.959E-07
2.	7.010E+00	-9.056E-08	---	---	-1.605E-07
2.	8.010E+00	-9.171E-08	---	---	1.382E-07
2.	9.010E+00	-6.385E-08	---	---	4.186E-07
3.	0.010E+00	-1.428E-08	---	---	5.717E-07
3.	1.010E+00	4.049E-08	---	---	5.216E-07
3.	2.010E+00	8.086E-08	---	---	2.839E-07
3.	3.010E+00	9.320E-08	---	---	-3.707E-08
3.	4.010E+00	7.529E-08	---	---	-3.200E-07
3.	5.010E+00	3.499E-08	---	---	-4.848E-07
3.	6.010E+00	-1.484E-08	---	---	-5.105E-07
3.	7.010E+00	6.047E-08	---	---	-4.006E-07
3.	8.010E+00	-8.900E-08	---	---	-1.680E-07
3.	9.010E+00	-9.056E-08	---	---	1.335E-07
4.	0.010E+00	-6.251E-08	---	---	4.223E-07
4.	1.010E+00	-1.310E-08	---	---	5.645E-07
4.	2.010E+00	4.027E-08	---	---	5.009E-07
4.	3.010E+00	7.670E-08	---	---	2.658E-07
4.	4.010E+00	9.024E-08	---	---	-3.567E-08
4.	5.010E+00	7.349E-08	---	---	-2.980E-07
4.	6.010E+00	3.531E-08	---	---	-4.630E-07
4.	7.010E+00	-1.320E-08	---	---	-5.051E-07
4.	8.010E+00	-5.885E-08	---	---	-4.067E-07
4.	9.010E+00	-8.781E-08	---	---	-1.712E-07
5.	0.000E+00	-8.934E-08	---	---	1.412E-07

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Figure 6-13.

oscillations will take a long time to decay. These results show that there is an "optimal" value for K_p from the standpoint of less oscillations and fast decay in the time response. Figure 6-11 shows that when K_p equals to 2.35 times its nominal value the response seems to be the best under the simulated conditions.

6.4 Effects of Varying K_r

Once a seemingly optimal value of K_p has been determined, it is necessary to investigate the effects of varying the other parameters of the controller. The time responses shown in Figs. 6-14 through 6-18 are for

$$K_i = \text{Nominal value}$$

$$K_p = 2.35 \times \text{Nominal value}$$

$$T = 0.1 \text{ sec}$$

$$K_{WT} = 100$$

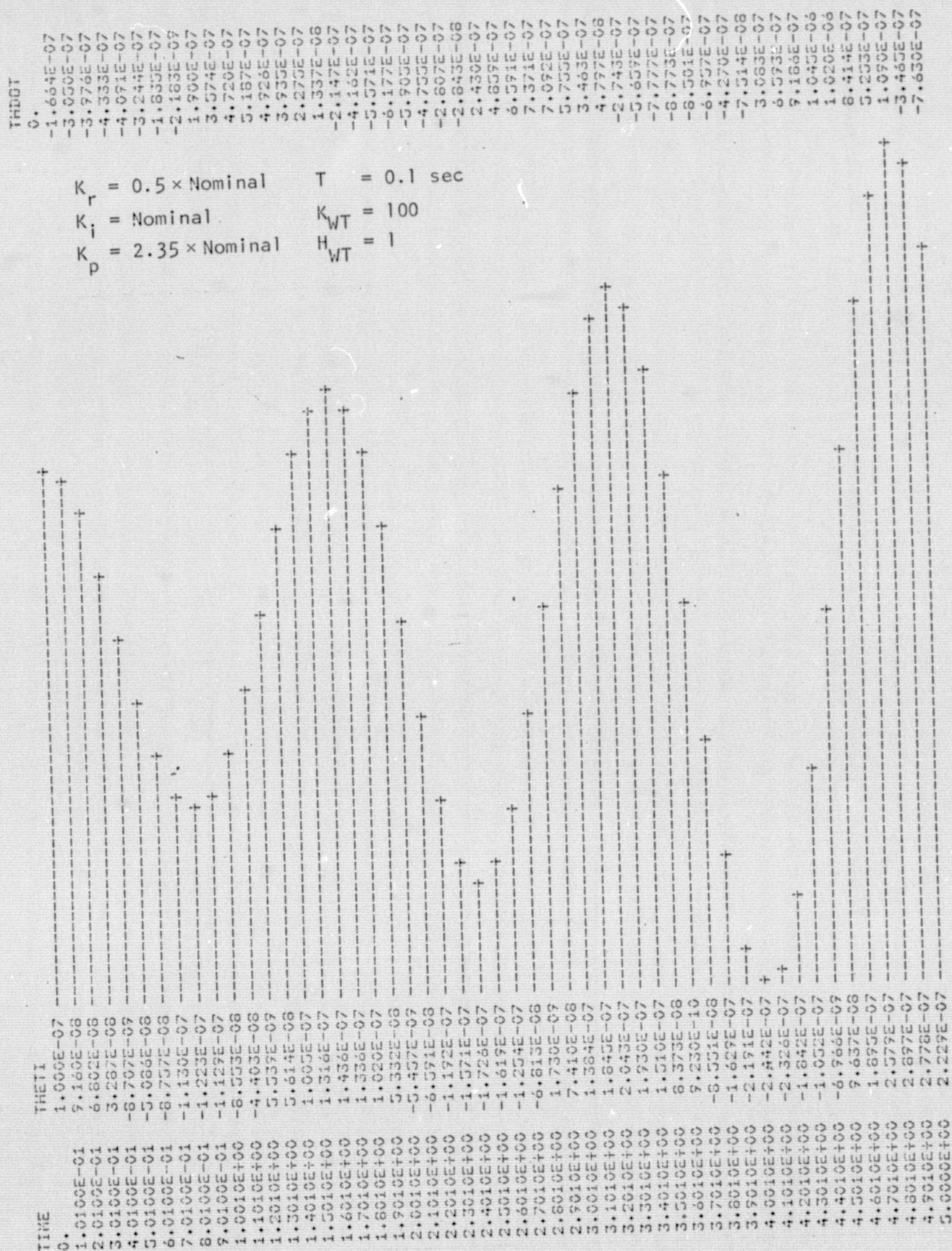
$$H_{WT} = 1$$

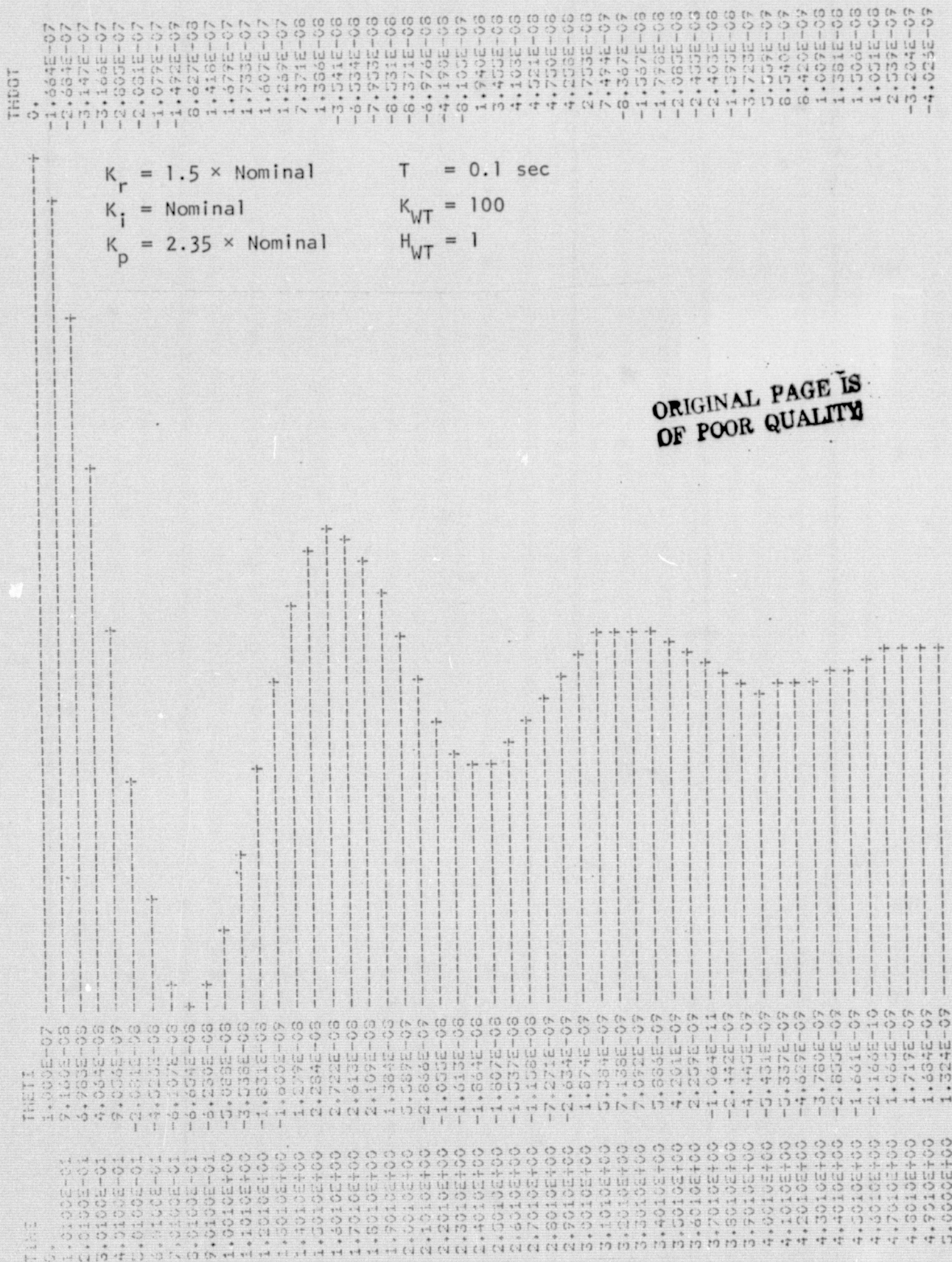
and K_r varies between 0.5 times to 3.5 times its nominal value.

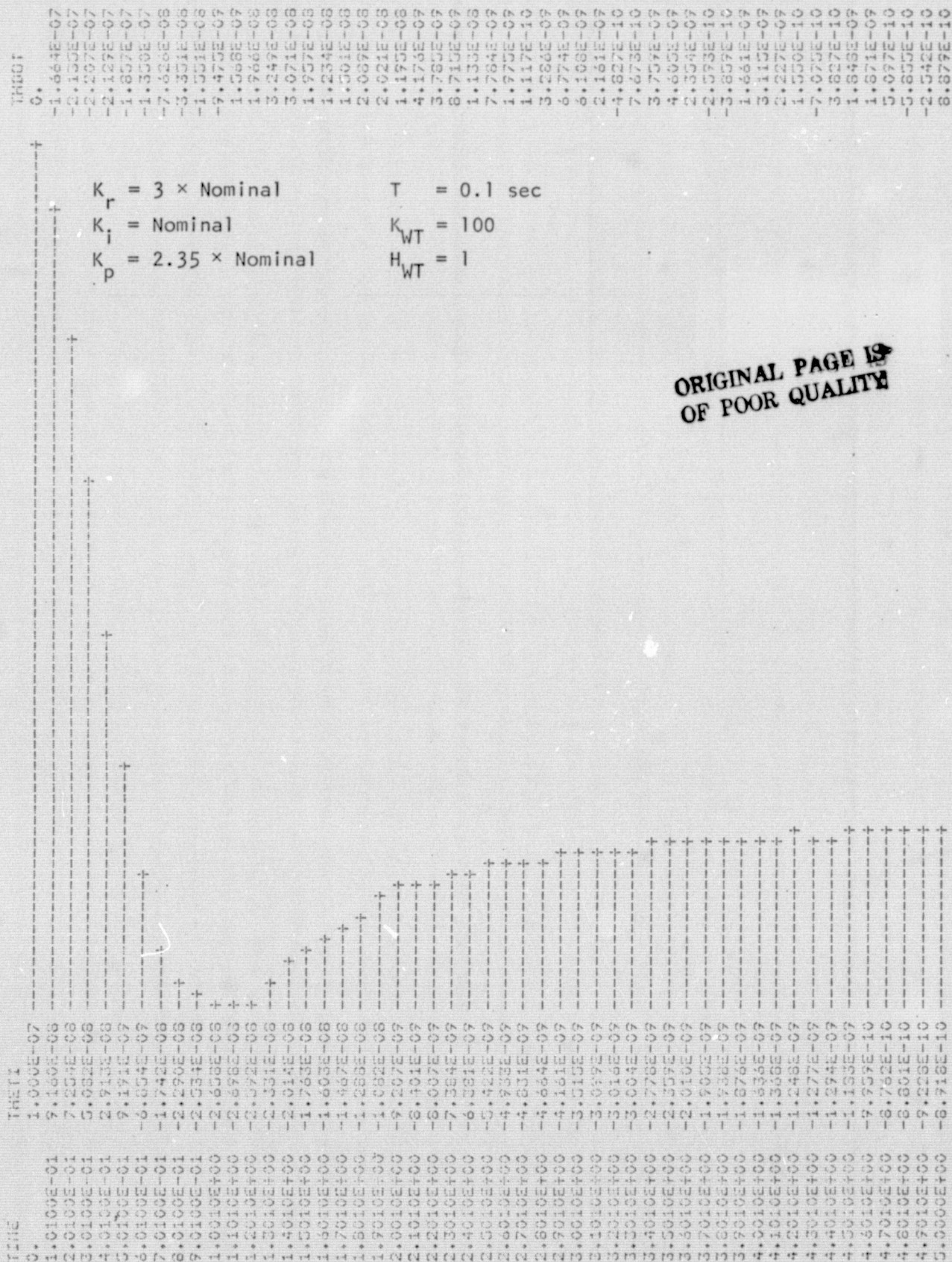
The time responses in these five figures show that as the value of K_r increases, the oscillations are reduced. However, for large values of K_r , the response is slower. It may seem that an appropriate range of K_r is between two times nominal to three times nominal. The steady-state error is also small with these values of K_r .

6.5 Effects of Varying K_i

Having selected the appropriate values of K_p and K_r in the initial round of trial-and-error design, the last parameter of the controller to be investigated is K_i . In this section the effects of varying K_i are investigated. Since the "optimal" value of K_r seems to lie between two







times nominal and three times nominal, two sets of simulations were run, one with $K_r = 2 \times \text{nominal}$ and the other with $K_r = 3 \times \text{nominal}$. Figures 6-19 through 6-22 illustrate the time responses of θ_i with

$$K_p = 2.35 \times \text{nominal}$$

$$K_r = 2 \times \text{nominal}$$

$$T = 0.1 \text{ sec}$$

$$K_{WT} = 100$$

$$H_{WT} = 1$$

and K_i varies between 0.5 times nominal to 2 times nominal. Figures 6-23 through 6-28 show the time responses for $K_r = 3 \times \text{nominal}$ and K_i varying between 0.125 times nominal to 2 times nominal, with all other parameters the same as above.

These simulation results indicate that for the sampling period of 0.1 sec the system is not too sensitive to the variation of K_i . In general, as K_i increases the response becomes more oscillatory. Although lower values of K_i give less overshoot, the steady-state error is actually larger. Therefore, a compromise has to be made between overshoot and steady-state error when making the selection on K_i . Comparing the responses in Figs. 6-23 through 6-27, it seems that $K_i = 1.25$ times nominal may be chosen from the standpoint of all-around performance.

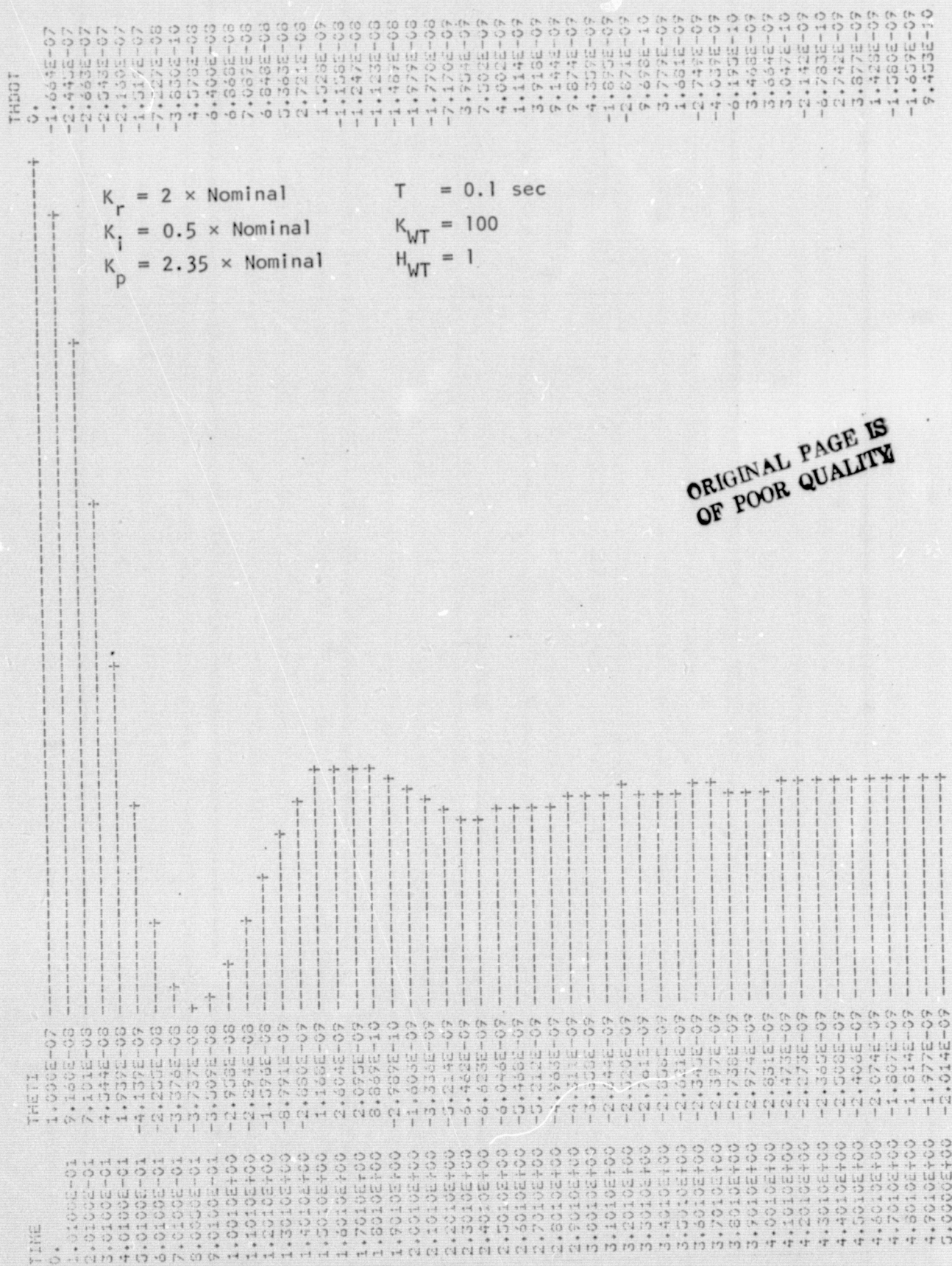
Figure 6-28 shows the time response of θ_i for the following parameters:

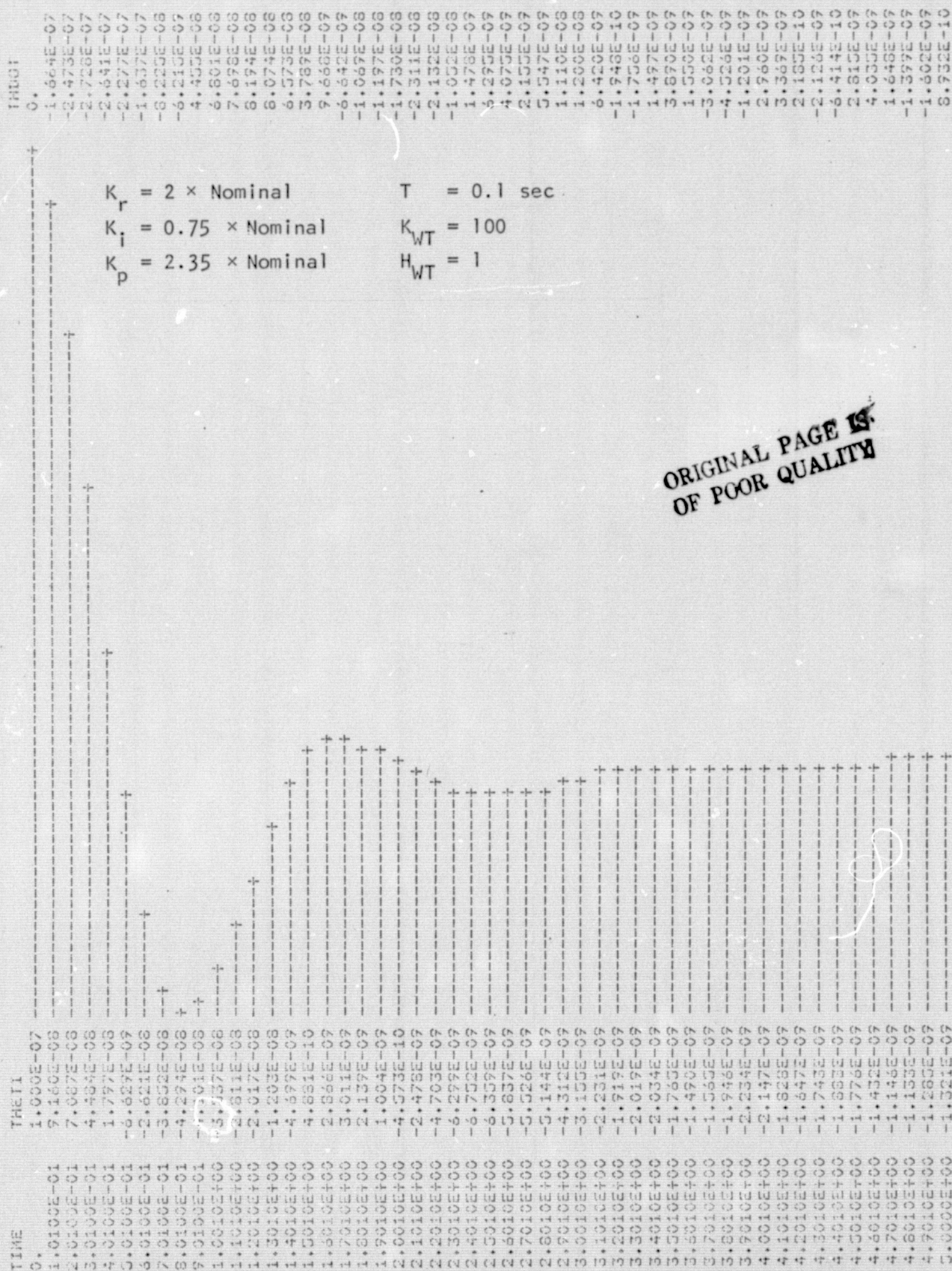
$$K_i = 1.25 \times \text{nominal}$$

$$K_p = 2.35 \times \text{nominal}$$

$$K_r = 2 \times \text{nominal}$$

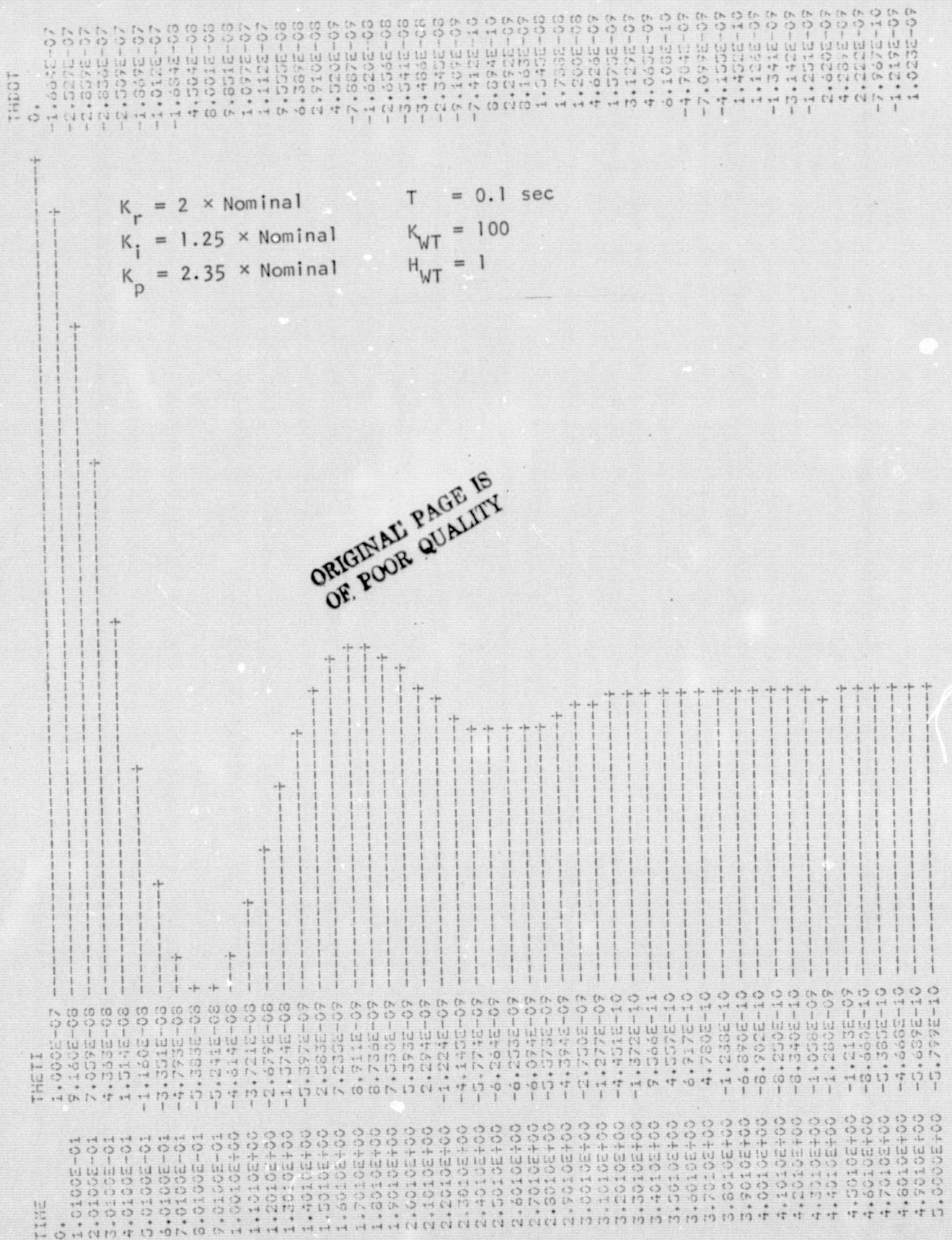
$$T = 0.1 \text{ sec}$$





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Figure 6-20.



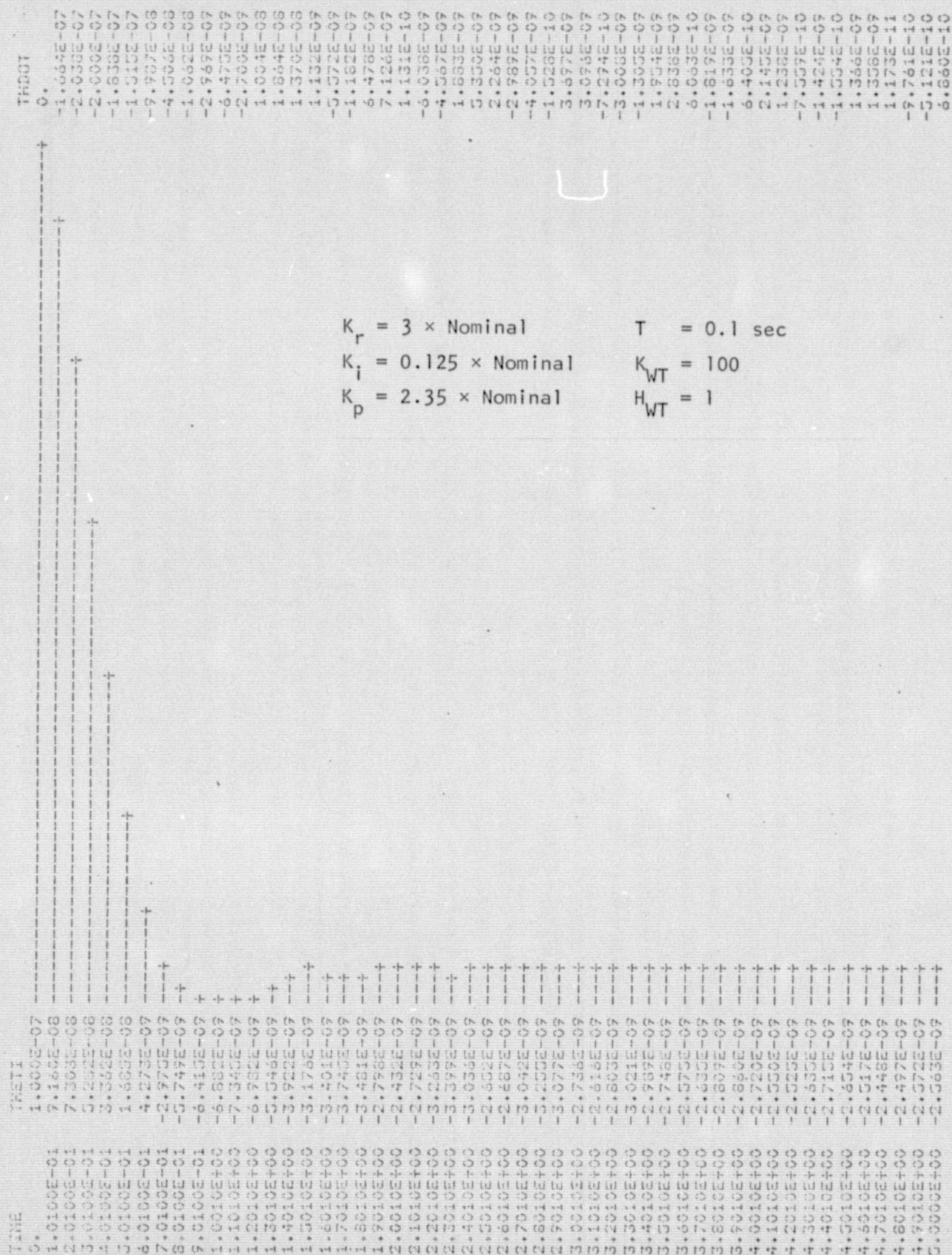
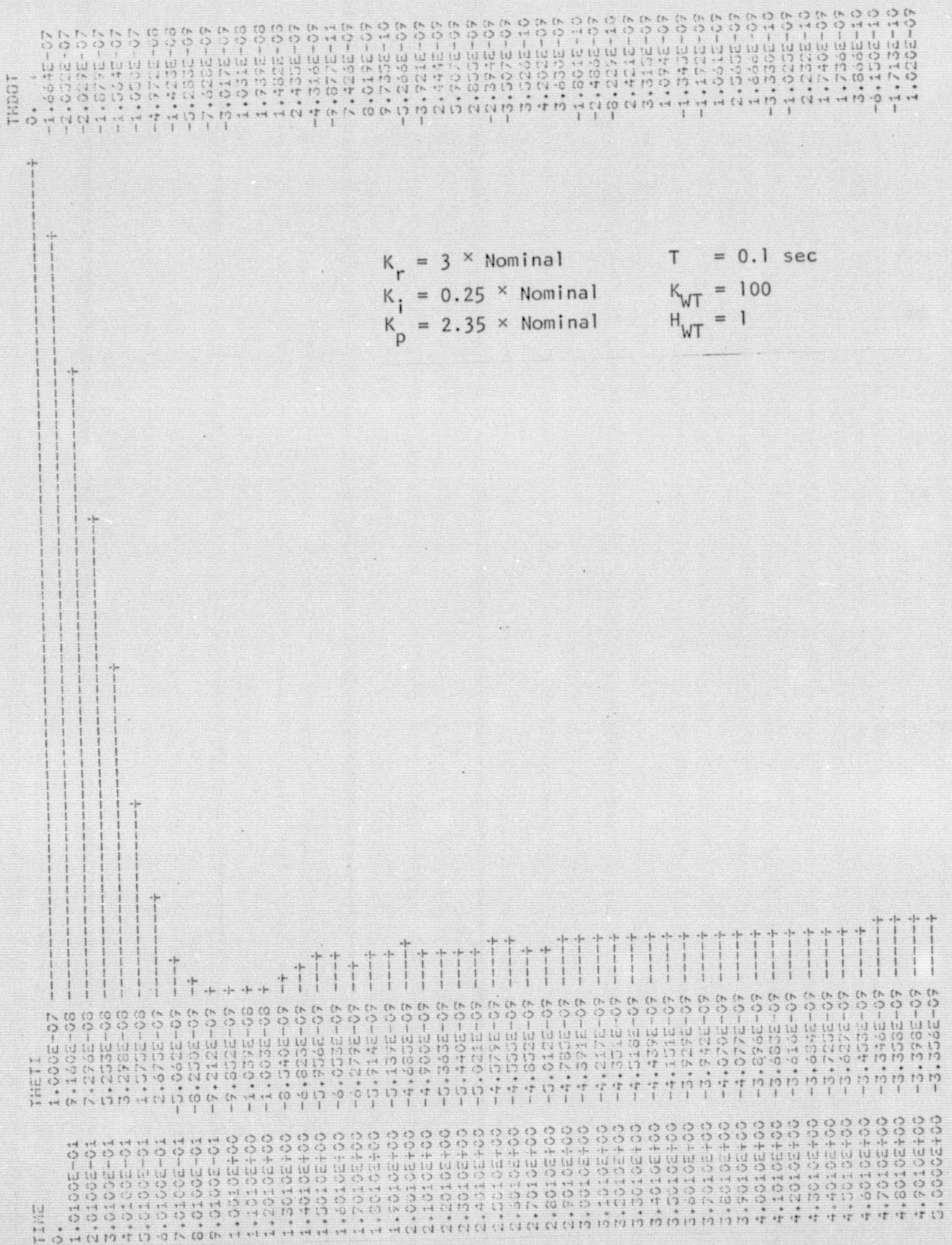
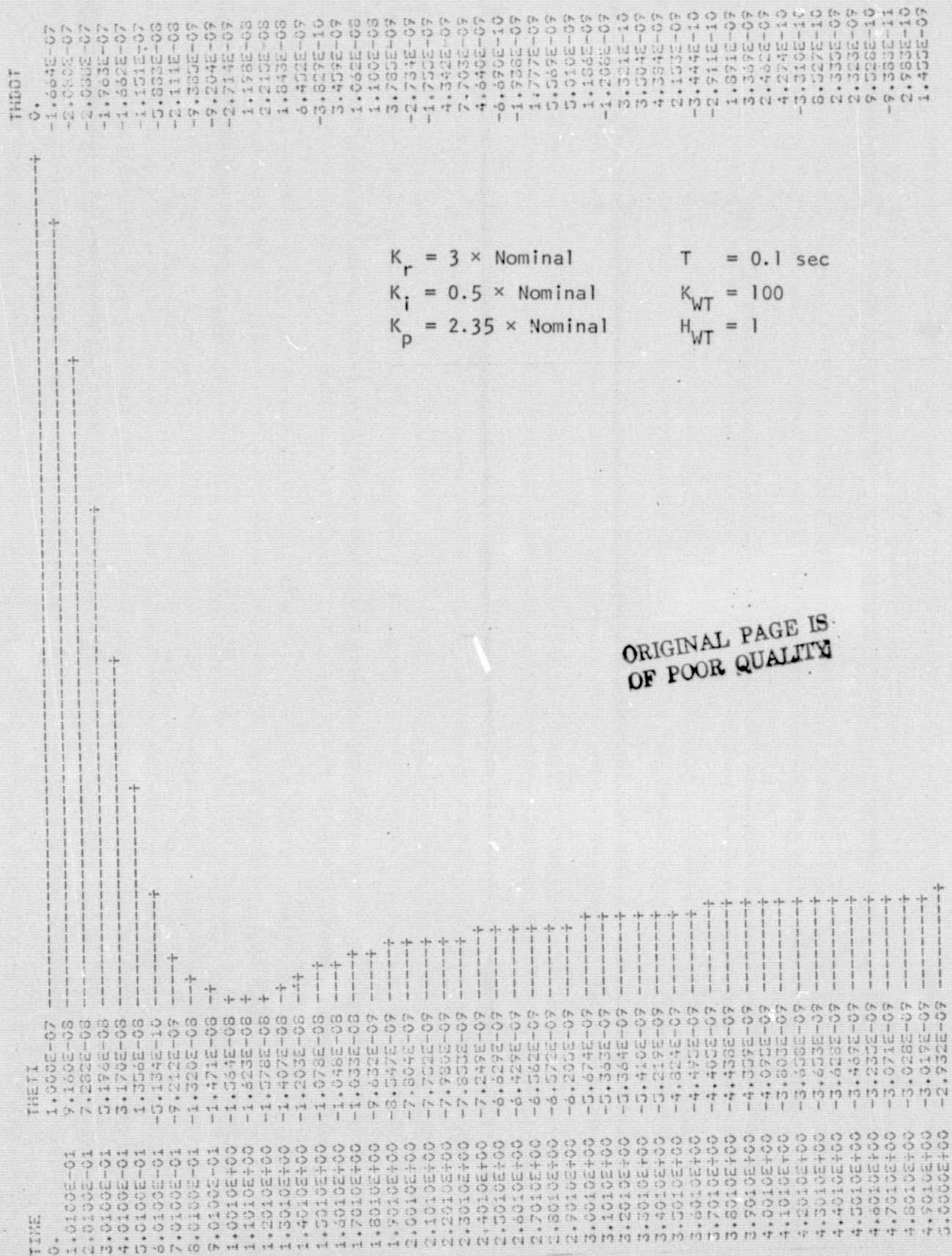
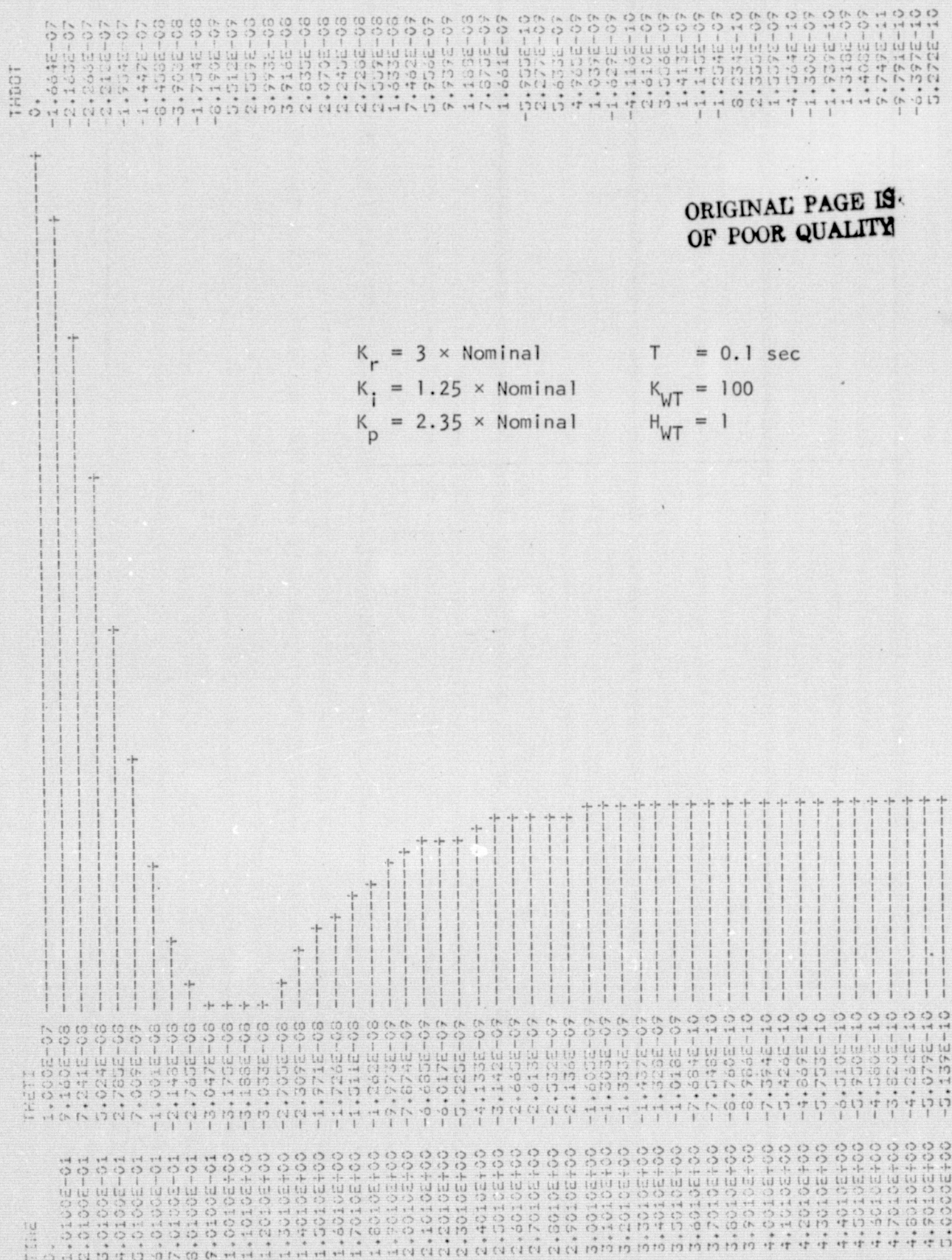
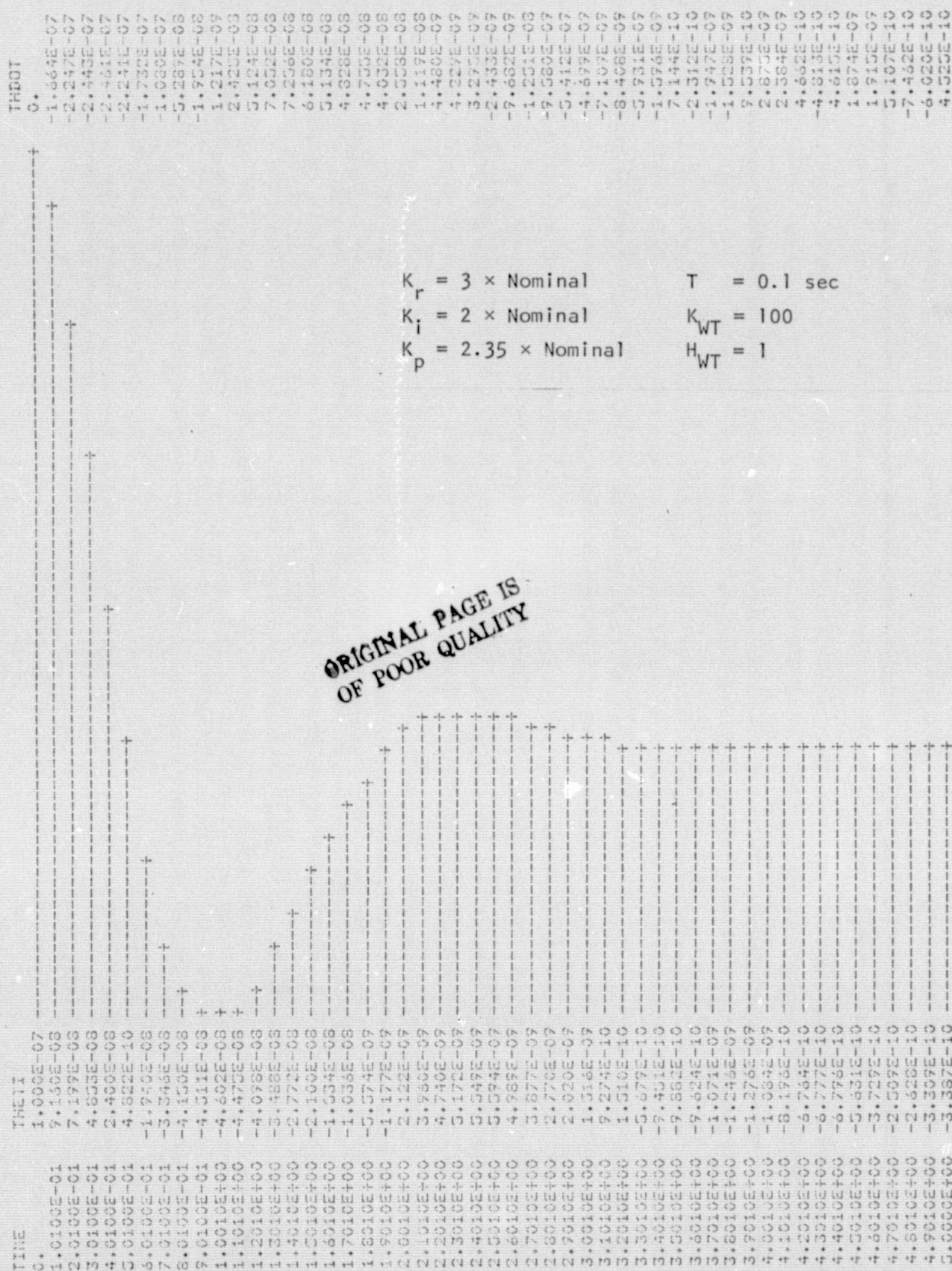


Figure 6-23.









TIME	TIME	TIME
0.1000E-01	1.000E-07	0.
1.0000E-01	7.166E-08	-1.664E-07
2.0000E-01	7.241E-08	-2.163E-07
3.0000E-01	5.874E-08	-2.766E-07
4.0000E-01	2.785E-08	-2.212E-07
5.0000E-01	7.007E-07	-1.954E-07
6.0000E-01	-1.001E-08	-1.447E-07
7.0000E-01	-2.148E-08	-8.458E-08
8.0000E-01	-2.765E-08	-3.903E-08
9.0000E-01	-3.047E-08	-1.754E-08
1.0010E+00	-3.175E-08	-8.190E-09
1.1010E+00	-3.188E-08	5.512E-09
1.2010E+00	-3.033E-08	2.559E-08
1.3010E+00	-2.705E-08	3.973E-08
1.4010E+00	-2.307E-08	3.916E-08
1.5010E+00	-1.971E-08	2.835E-08
1.6010E+00	-1.728E-08	2.070E-08
1.7010E+00	-1.511E-08	2.245E-08
1.8010E+00	-1.267E-08	2.728E-08
1.9010E+00	-9.773E-09	2.557E-08
2.0010E+00	-7.874E-09	1.633E-08
2.1010E+00	-6.685E-09	7.462E-09
2.2010E+00	-6.017E-09	5.956E-09
2.3010E+00	-5.225E-09	9.937E-09
2.4010E+00	-4.133E-09	1.188E-08
2.5010E+00	-3.142E-09	7.875E-09
2.6010E+00	-2.665E-09	1.661E-09
2.7010E+00	-2.613E-09	1.039E-09
2.8010E+00	-2.532E-09	-1.627E-09
2.9010E+00	-2.436E-09	-4.116E-10
3.0010E+00	-1.605E-09	2.610E-09
3.1010E+00	-1.303E-09	3.556E-09
3.2010E+00	-1.333E-09	1.413E-09
3.3010E+00	-1.437E-09	-1.145E-09
3.4010E+00	-1.328E-09	-1.254E-09
3.5010E+00	-1.018E-09	8.234E-10
3.6010E+00	-7.684E-10	2.355E-09
3.7010E+00	-7.548E-10	1.557E-09
3.8010E+00	-8.766E-10	-4.564E-10
3.9010E+00	-8.988E-10	-1.300E-09
4.0010E+00	-7.374E-10	-1.937E-10
4.1010E+00	-5.426E-10	1.318E-09
4.2010E+00	-4.889E-10	1.408E-09
4.3010E+00	-5.753E-10	9.747E-11
4.4010E+00	-6.510E-10	-9.791E-10
4.5010E+00	-5.950E-10	-6.377E-10
4.6010E+00	-4.580E-10	5.391E-10
4.7010E+00	-3.820E-10	1.066E-09
4.8010E+00	-4.262E-10	4.264E-10
4.9010E+00	-3.556E-10	-5.560E-10
5.0010E+00	-3.620E-10	-7.117E-10
5.1010E+00	-4.259E-10	3.507E-11
5.2010E+00	-4.602E-10	7.124E-10
5.3010E+00	-4.228E-10	5.407E-10
5.4010E+00	-3.577E-10	-1.915E-10
5.5010E+00	-3.419E-10	-5.847E-10
5.6010E+00	-3.809E-10	-2.311E-10
5.7010E+00	-4.221E-10	3.736E-10
5.8010E+00	-4.151E-10	5.016E-10
5.9010E+00	-3.711E-10	5.748E-11
6.0010E+00	-3.429E-10	-3.857E-10
6.1010E+00	-3.573E-10	-3.208E-10
6.2010E+00	-3.749E-10	1.172E-10
6.3010E+00	-4.052E-10	3.808E-10
6.4010E+00	-3.802E-10	1.852E-10
6.5010E+00	-3.517E-10	-1.932E-10
6.6010E+00	-3.520E-10	-2.997E-10
6.7010E+00	-3.768E-10	-4.416E-11
6.8010E+00	-3.942E-10	2.378E-10
6.9010E+00	-3.845E-10	2.181E-10
7.0010E+00	-3.616E-10	-4.640E-11
7.1010E+00	-3.528E-10	-2.244E-10
7.2010E+00	-3.604E-10	-1.215E-10
7.3010E+00	-3.837E-10	1.115E-10
7.4010E+00	-3.844E-10	1.915E-10
7.5010E+00	-3.672E-10	4.376E-11
7.6010E+00	-3.573E-10	-1.357E-10
7.7010E+00	-3.617E-10	-1.377E-10
7.8010E+00	-3.757E-10	1.969E-11
7.9010E+00	-3.816E-10	1.376E-10
8.0010E+00	-3.737E-10	8.432E-11
8.1010E+00	-3.626E-10	-5.907E-11
8.2010E+00	-3.613E-10	-1.176E-10
8.3010E+00	-3.701E-10	-3.385E-11
8.4010E+00	-3.778E-10	7.771E-11
8.5010E+00	-3.755E-10	8.890E-11
8.6010E+00	-3.870E-10	-4.716E-12
8.7010E+00	-3.626E-10	-8.216E-11
8.8010E+00	-3.671E-10	-5.572E-11
8.9010E+00	-3.741E-10	3.167E-11
9.0010E+00	-3.753E-10	7.307E-11
9.1010E+00	-3.701E-10	2.588E-11
9.2010E+00	-3.651E-10	-4.554E-11
9.3010E+00	-3.609E-10	
9.4010E+00	-3.717E-10	

$$K_r = 3 \times \text{Nominal}$$

$$T = 0.1 \text{ sec}$$

$$K_i = 1.25 \times \text{Nominal}$$

$$K_{WT} = 100$$

$$K_p = 2.35 \times \text{Nominal}$$

$$H_{WT} = 1$$

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Figure 6-28.

$$K_{WT} = 100$$

$$H_{WT} = 1$$

The response is extended for the time period up to 9.7 seconds to show that in the steady-state practically no oscillations take place.

6.6 Effects of Varying The Sampling Period

Thus far all the simulations have been carried out with a sampling period of 0.1 sec. Although the original system with the nominal values for K_p , K_i and K_r is unstable with $T = 0.1$ sec, Fig. 6-28 shows that the digital IPS can indeed be stabilized and yield satisfactory responses by fine tuning the controller parameters.

It is of interest to investigate if the digital IPS can be stabilized with the given controller configuration with higher sampling periods. Figures 6-29 and 6-30 illustrate the θ_i responses for $T = 0.2$ sec and 0.3 sec, respectively. The other relevant system parameters are:

$$K_p = 2.35 \text{ times nominal}$$

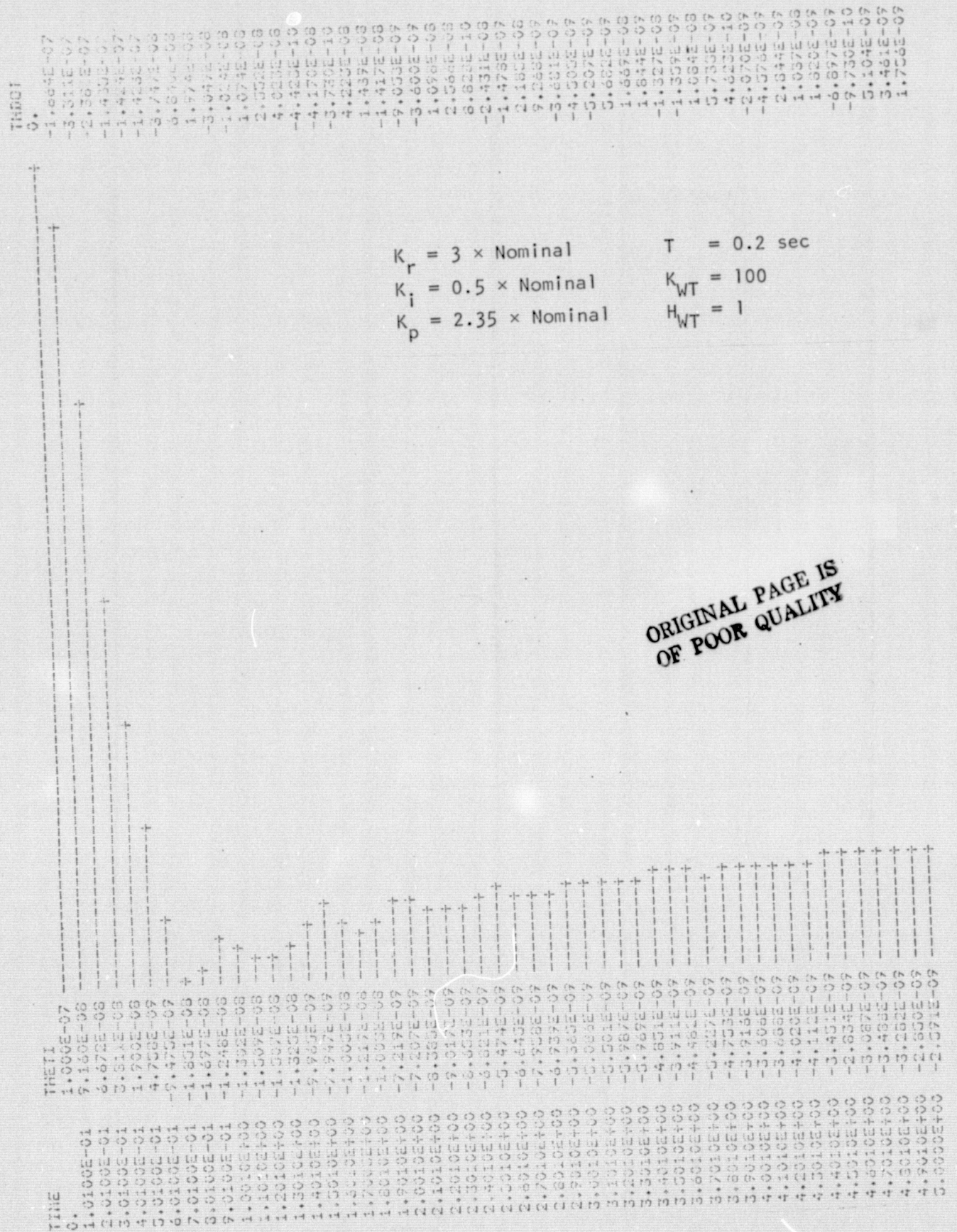
$$K_r = 3 \text{ times nominal}$$

$$K_i = 0.5 \text{ times nominal}$$

$$K_{WT} = 100$$

$$H_{WT} = 1$$

Note that the values of K_p , K_r and K_i were chosen so that the system performs best with $T = 0.1$ sec. Figure 6-29 shows that when $T = 0.2$ sec the system is stable, although the response is slightly oscillatory during the transient state. However, the system is unstable for $T = 0.3$ sec (Fig. 6-30).



$$K_r = 3 \times \text{Nominal}$$

$$K_i = 0.5 \times \text{Nominal}$$

$$K_p = 2.35 \times \text{Nominal}$$

$$T = 0.2 \text{ sec}$$

$$K_{WT} = 100$$

$$H_{WT} = 1$$

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6.7 Design of the Controller Parameters for $T = 0.3$ sec (K_r Varies)

It is apparent that the controller parameters that are suitable for the sampling period of $T = 0.1$ sec may not be the best for higher sampling periods. The objective now is to find a set of controller parameters so that the system has a satisfactory response for $T = 0.3$ sec. We shall first fix the values of K_p and K_i and vary K_r . Figures 6-31 through 6-35 show the responses of θ_i when K_r varies between 1.25 times to 2 times its nominal value, and

$$K_p = 2.35 \text{ times nominal}$$

$$K_i = 0.5 \text{ times nominal}$$

$$K_{WT} = 100$$

$$H_{WT} = 1$$

$$T = 0.3 \text{ sec}$$

It is important to note that while the system is stable over a rather wide range of values for K_r when $T = 0.1$ sec, when $T = 0.3$ sec, the system becomes very sensitive to the value of K_r . Figures 6-31 and 6-35 show that for both small ($K_r = 1.25$ times nominal) and large (2 times nominal) values of K_r the response is very oscillatory. The response in Fig. 6-35 is actually unstable. Figures 6-32 and 6-33 show that $K_r = 1.5 \times$ nominal or $1.65 \times$ nominal seem to be the best choices for the specific situation. The response in Fig. 6-34 for $K_r = 1.75 \times$ nominal becomes slightly erratic at the 5-second mark. The simulation results indicate that at least the digital IPS can be stabilized for $T = 0.3$ sec.

6.8 Design of the Controller Parameters for $T = 0.3$ sec (K_p Varies)

Since smaller values of K_i would result in slower response, it was determined to vary only the value of K_p in order to improve on the system

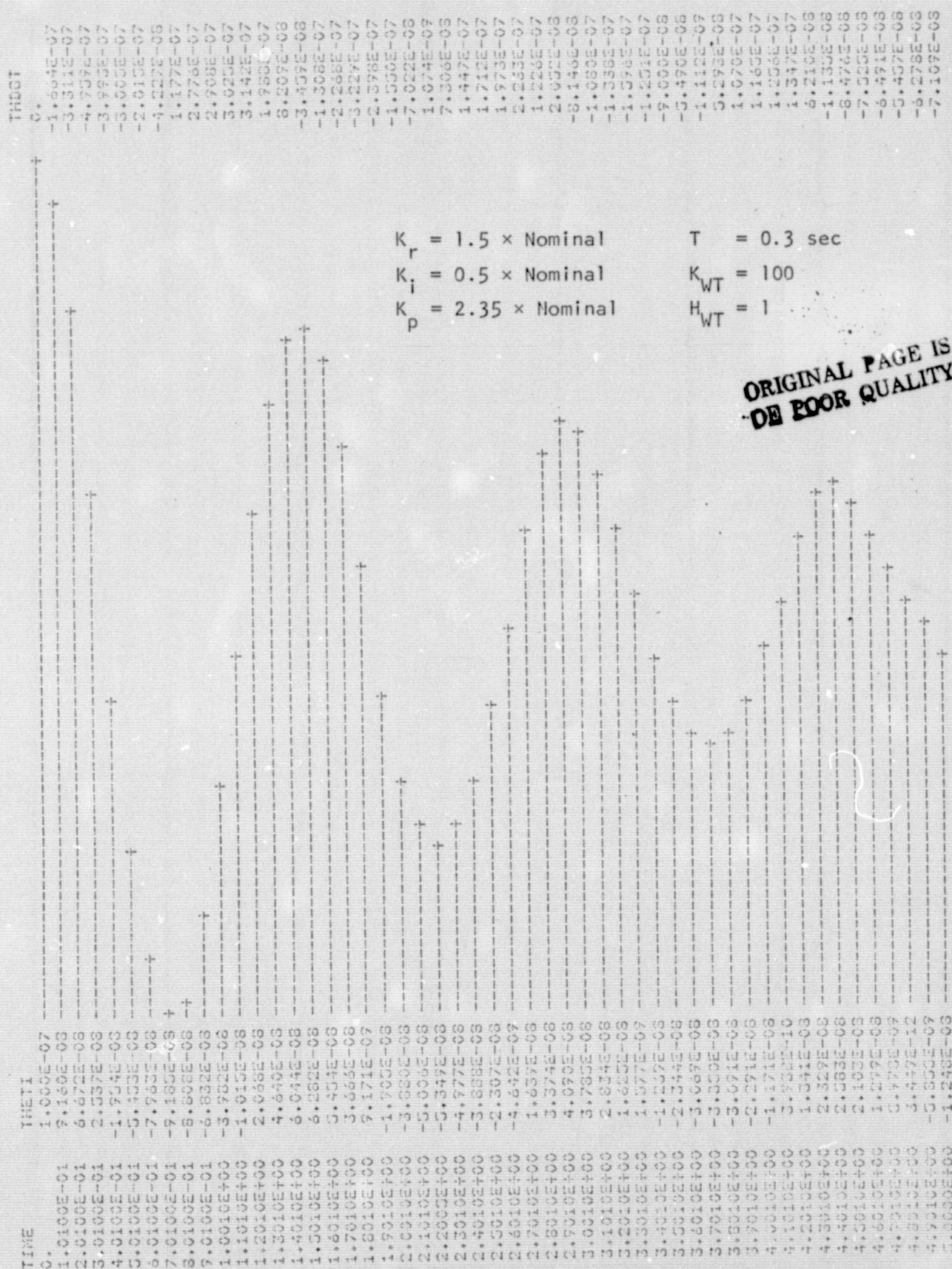
$$K_r = 1.25 \times \text{Nominal} \quad T = 0.3 \text{ sec}$$

$$K_i = 0.5 \times \text{Nominal} \quad K_{WT} = 100$$

$$K_p = 2.35 \times \text{Nominal} \quad H_{WT} = 1$$

NAME	FILE	THROT
0.	1.000E-07	0.
1.010E-01	9.160E-08	-1.664E-07
2.010E-01	6.672E-08	-3.31E-07
3.010E-01	2.571E-08	-4.939E-07
4.010E-01	-2.000E-08	-4.234E-07
5.010E-01	-5.931E-08	-3.485E-07
6.010E-01	-9.040E-08	-2.736E-07
7.010E-01	-1.088E-07	-8.870E-08
8.010E-01	-1.088E-07	9.744E-08
9.010E-01	-8.910E-08	2.837E-07
1.0010E+00	-5.764E-08	3.472E-07
1.1010E+00	-2.022E-08	4.033E-07
1.2010E+00	2.302E-08	4.625E-07
1.3010E+00	6.243E-08	5.266E-07
1.4010E+00	8.775E-08	1.688E-07
1.5010E+00	9.878E-08	4.189E-08
1.6010E+00	9.488E-08	-1.242E-07
1.7010E+00	7.410E-08	-2.904E-07
1.8010E+00	3.679E-08	-4.572E-07
1.9010E+00	-6.284E-09	-4.023E-07
2.0010E+00	-4.375E-08	-2.465E-07
2.1010E+00	-7.559E-08	-2.904E-07
2.2010E+00	-9.663E-08	-1.295E-07
2.3010E+00	-1.015E-07	3.255E-08
2.4010E+00	-9.012E-08	1.947E-07
2.5010E+00	-9.580E-08	2.910E-07
2.6010E+00	3.193E-08	3.865E-07
2.7010E+00	1.150E-08	4.820E-07
2.8010E+00	5.288E-08	5.432E-07
2.9010E+00	8.014E-08	2.019E-07
3.0010E+00	9.328E-08	8.063E-08
3.1010E+00	9.204E-08	-8.414E-08
3.2010E+00	7.644E-08	-3.092E-07
3.3010E+00	4.631E-08	-3.632E-07
3.4010E+00	9.291E-09	-3.552E-07
3.5010E+00	-2.675E-08	-3.453E-07
3.6010E+00	-8.176E-08	-1.789E-07
3.7010E+00	-6.803E-08	1.572E-07
3.8010E+00	-9.754E-08	2.554E-07
3.9010E+00	-9.032E-08	3.524E-07
4.0010E+00	-6.950E-08	4.504E-07
4.1010E+00	-3.913E-08	5.474E-07
4.2010E+00	1.035E-09	6.447E-07
4.3010E+00	4.034E-08	7.427E-07
4.4010E+00	6.857E-08	8.406E-07
4.5010E+00	8.511E-08	9.385E-07
4.6010E+00	8.894E-08	1.036E-07
4.7010E+00	7.688E-08	-3.119E-08
4.8010E+00	5.486E-08	-1.705E-07
4.9010E+00	2.249E-08	-3.098E-07
5.0000E+00	-1.209E-08	-3.566E-07
		-3.620E-07

Figure 6-31.



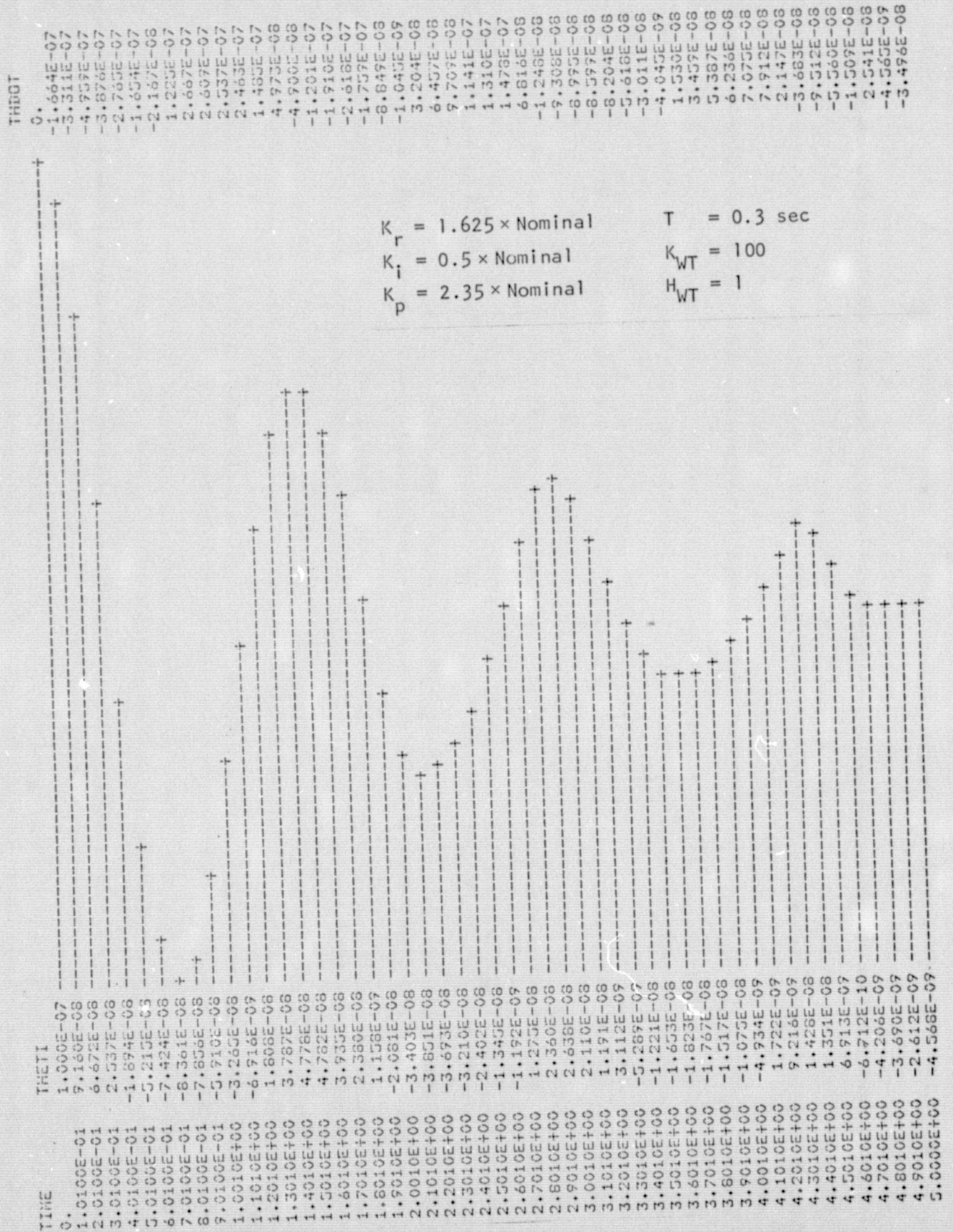
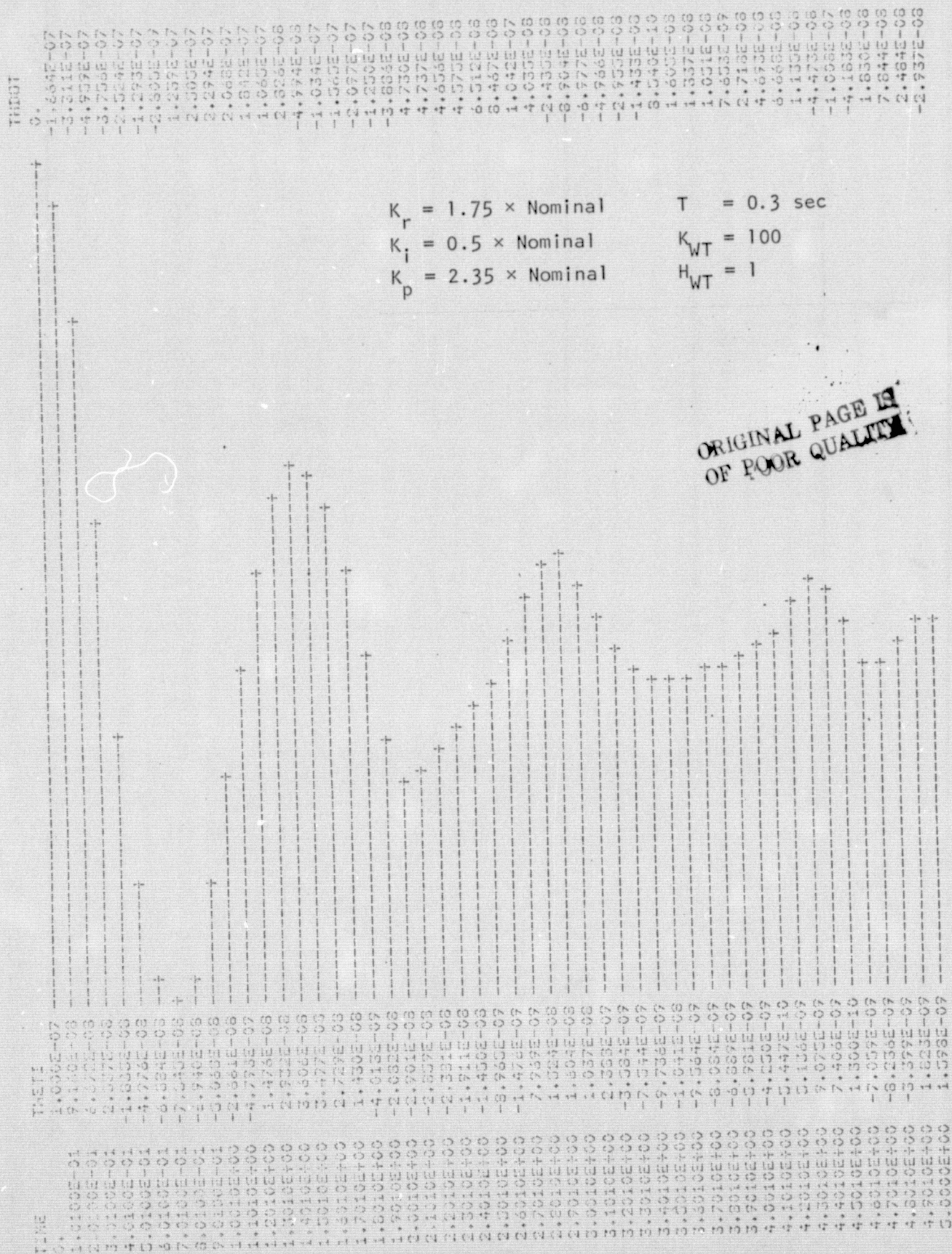
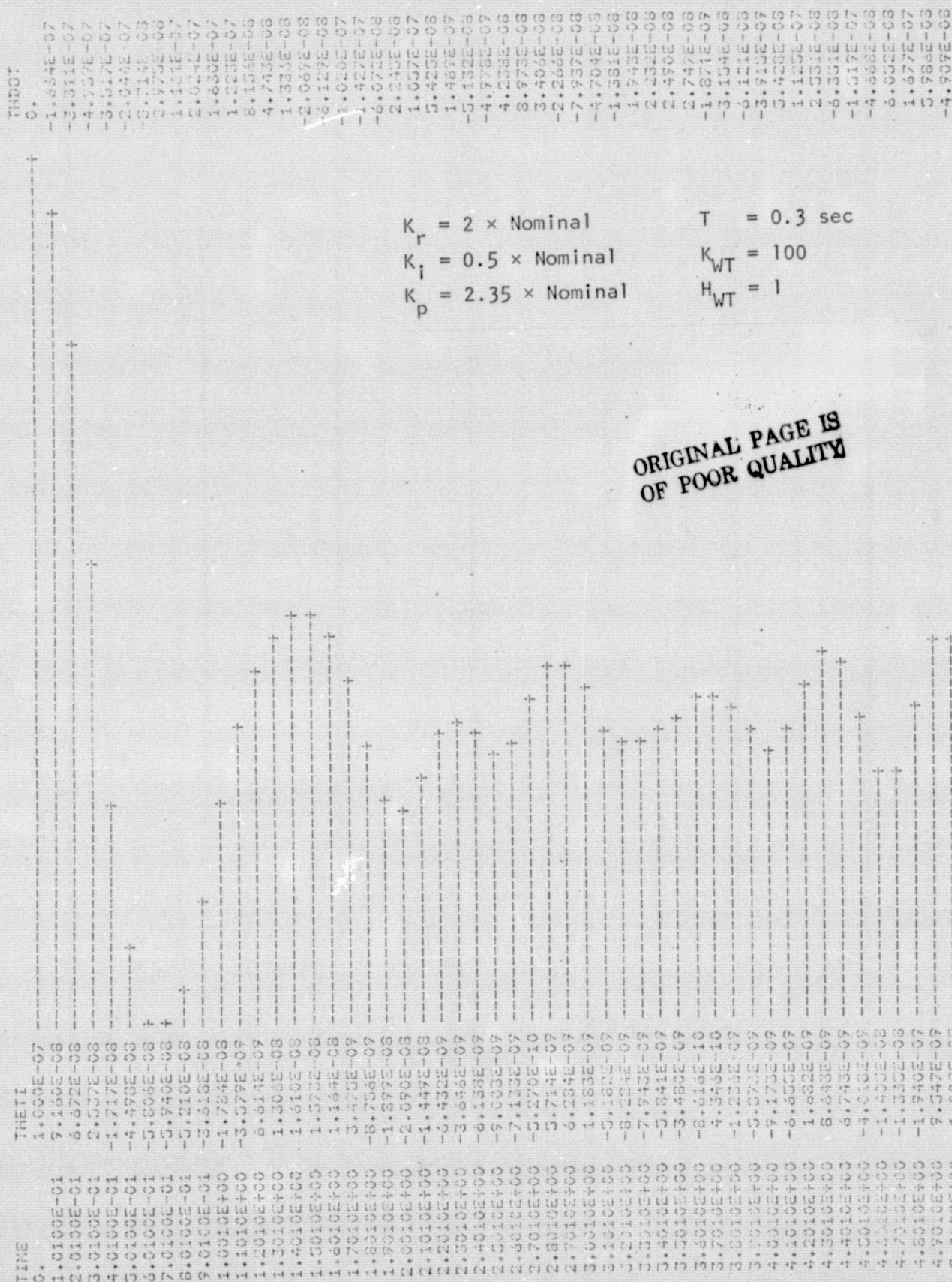


Figure 6-33.





response for $T = 0.3$ sec. Figures 6-36 through 6-39 show the θ_i responses for the following system parameters:

$$K_i = 0.5 \text{ times nominal}$$

$$K_r = 1.65 \text{ times nominal}$$

$$K_{WT} = 100$$

$$H_{WT} = 1$$

$$T = 0.3 \text{ sec}$$

and K_p varies between 0.75 times nominal to 3 times nominal. These simulation results show that the $K_p = 1.25 \times \text{nominal}$ case is the best among the cases studied.

Figure 6-40 illustrates the θ_i response of the above case for a longer time interval. An oscillation amplitude between -2×10^{-9} to 2×10^{-9} seems to exist. This extremely small oscillation may be due to the digital simulation which has an integration interval of 0.02 sec.

Figure 6-41 shows a case that the system response seems to be diverging after a sufficiently long period of time.

6.9 Effects of Larger Sampling Periods

Figures 6-42 and 6-43 illustrate the system responses when the sampling period is increased to 0.325 and 0.35, respectively. The system is unstable under these conditions. When the sampling period is 0.5 sec, many simulation runs with various controller parameters did not yield a stable system. Figure 6-44 illustrates a typical unstable response for $T = 0.5$ sec.

6.10 Conclusions

Due to the nonlinear nature of the digital IPS system, the design carried out in the chapter is basically a trial-and-error effort. The simulation results show that the system can have fairly well-behaved

response for $T = 0.1$ sec. For $T = 0.3$ sec, the system seems to perform well with the following set of controller parameters:

$$K_p = 1.25 \text{ times nominal}$$

$$K_r = 0.5 \text{ times nominal}$$

$$K_i = 1.65 \text{ times nominal}$$

Although it may be possible to stabilize the system for sampling periods greater than 0.3 sec, fine tuning the controller parameters to achieve this is quite difficult, and the sensitivity of the system may be poor.

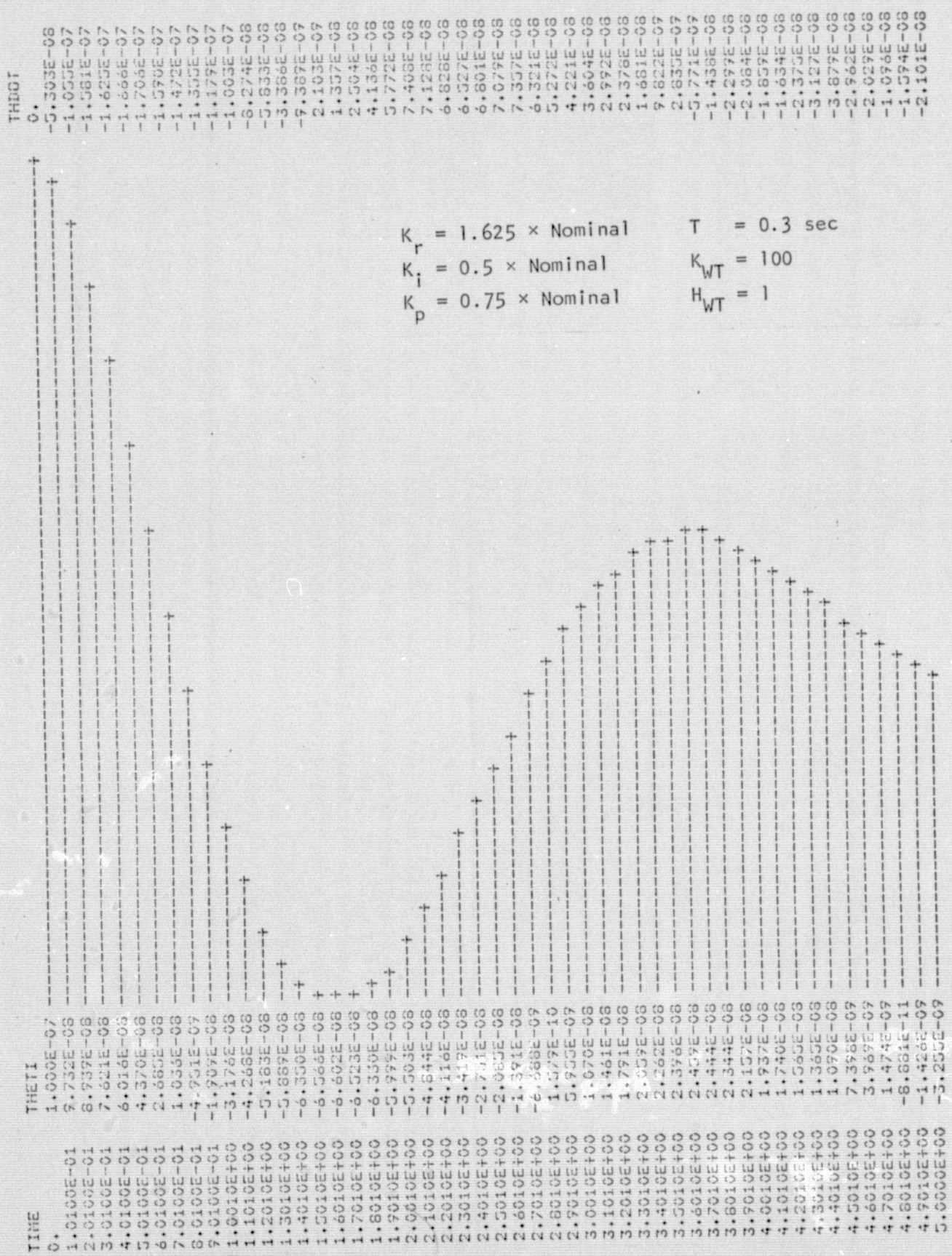


Figure 6-36.

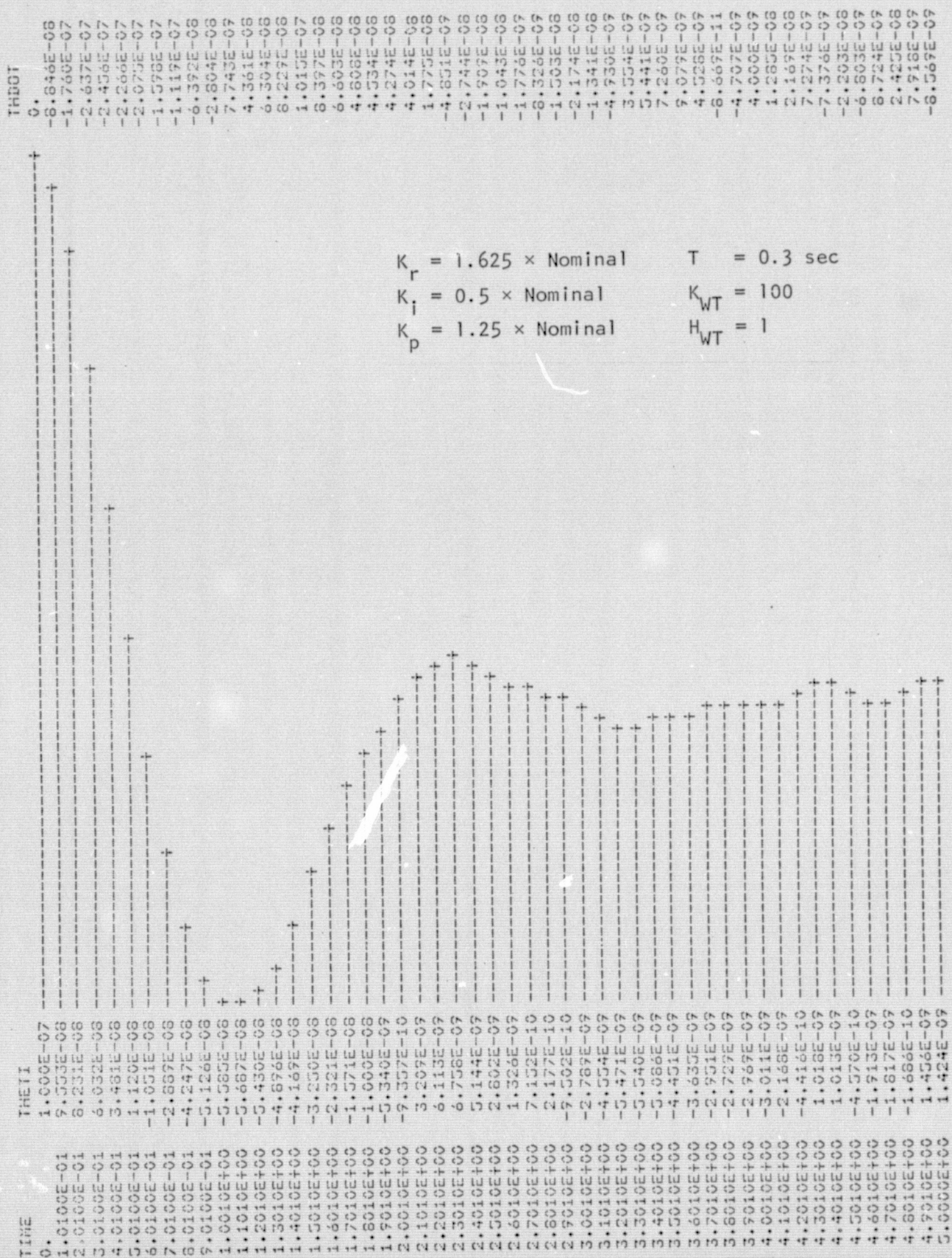
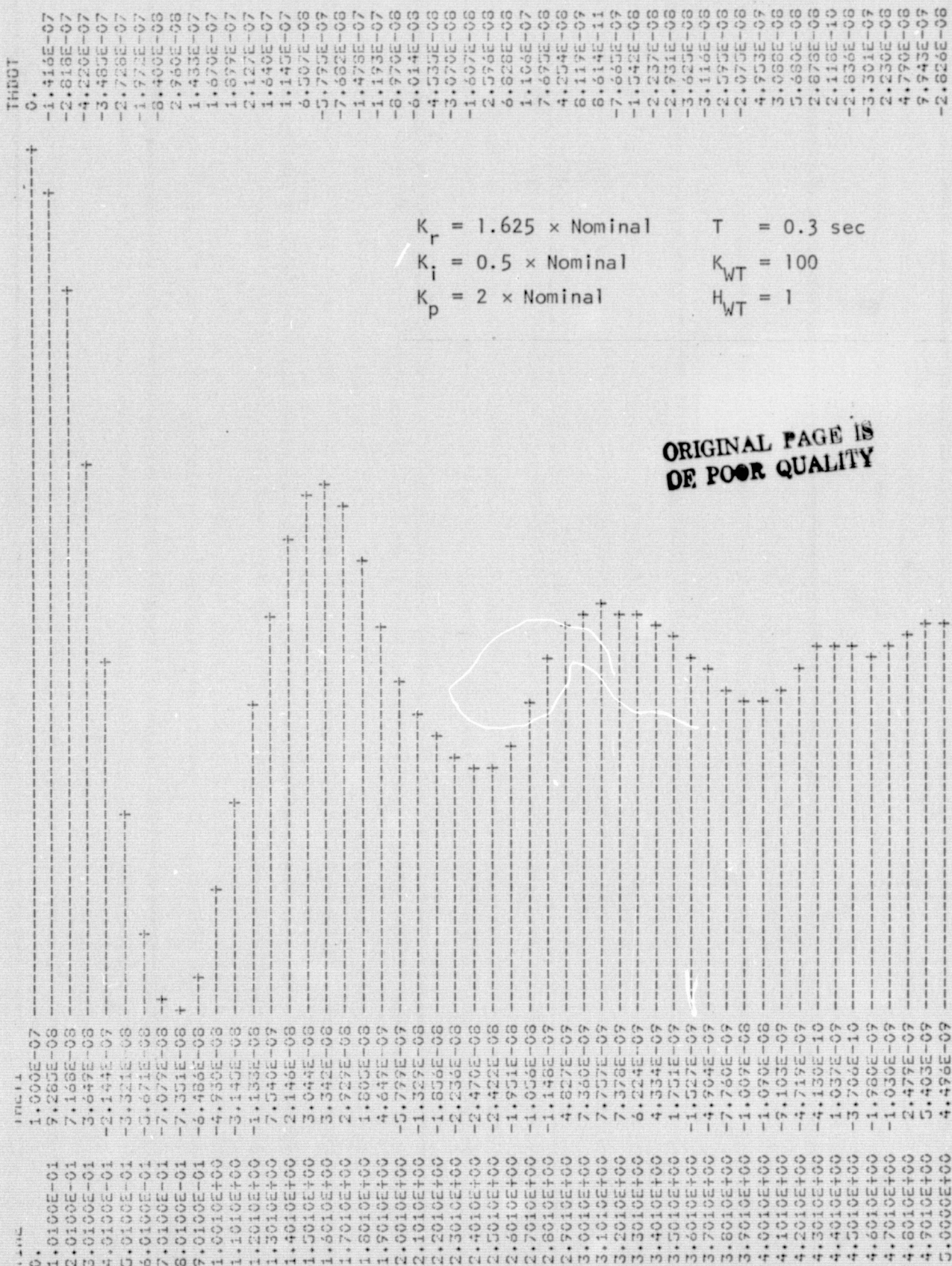
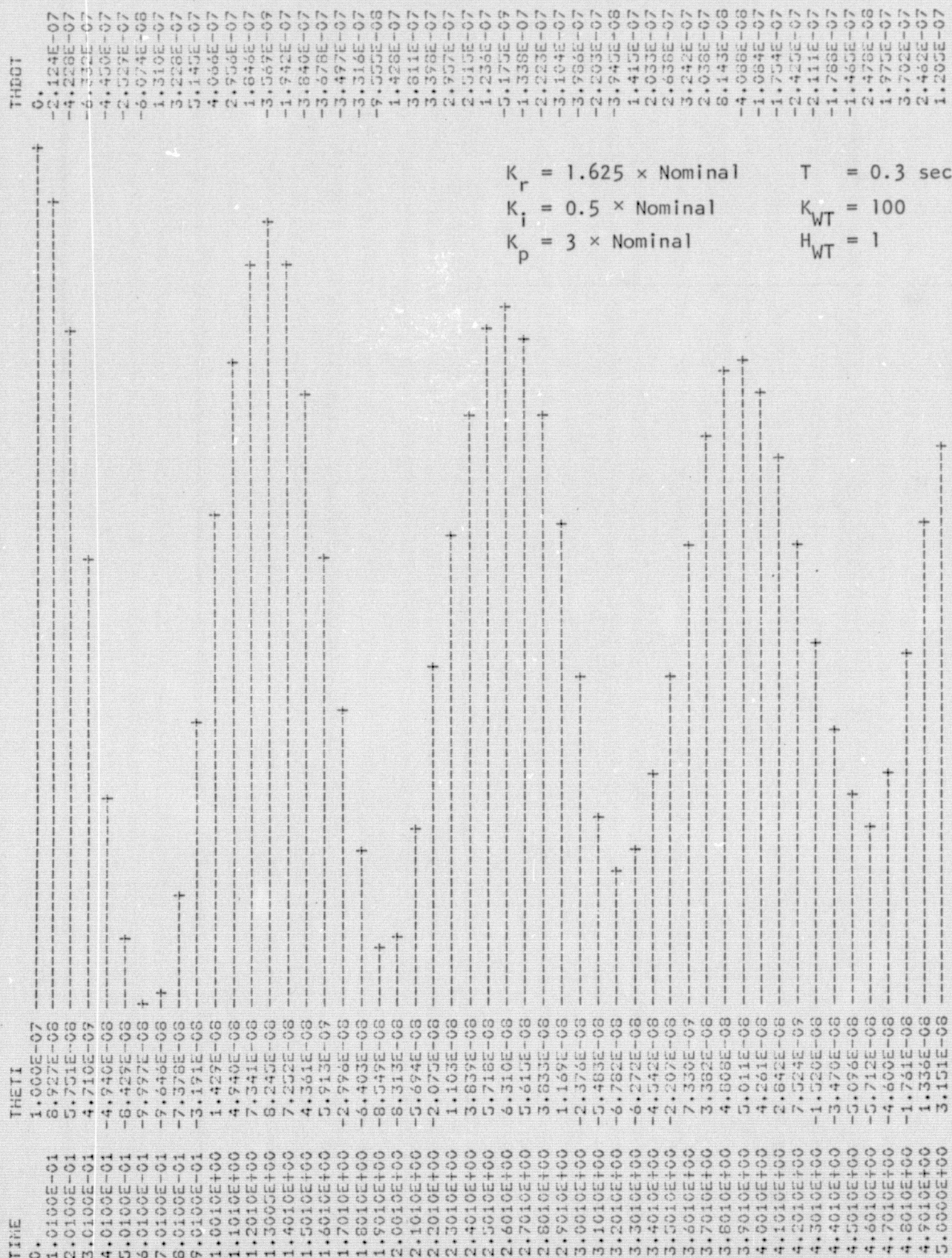


Figure 6-37.





TIME	TIME	TIME	TIME
0.	1.000E-07	0.	8.846E-08
1.010E-01	9.503E-08	1.010E-01	-1.760E-07
2.010E-01	8.231E-08	2.010E-01	-2.637E-07
3.010E-01	6.831E-08	3.010E-01	-2.474E-07
4.010E-01	5.462E-08	4.010E-01	-2.342E-07
5.010E-01	4.043E-08	5.010E-01	-2.170E-07
6.010E-01	2.723E-08	6.010E-01	-1.874E-07
7.010E-01	1.466E-08	7.010E-01	-1.174E-07
8.010E-01	-4.611E-08	8.010E-01	-6.751E-08
9.010E-01	-5.559E-08	9.010E-01	-2.872E-08
1.0010E+00	-6.046E-08	1.0010E+00	1.200E-08
1.1010E+00	-6.130E-08	1.1010E+00	5.281E-08
1.2010E+00	-5.806E-08	1.2010E+00	7.380E-08
1.3010E+00	-5.172E-08	1.3010E+00	9.407E-08
1.4010E+00	-4.330E-08	1.4010E+00	1.154E-07
1.5010E+00	-3.280E-08	1.5010E+00	9.738E-08
1.6010E+00	-2.214E-08	1.6010E+00	7.900E-08
1.7010E+00	-1.332E-08	1.7010E+00	6.060E-08
1.8010E+00	-6.344E-09	1.8010E+00	5.280E-08
1.9010E+00	-6.770E-10	1.9010E+00	4.507E-08
2.0010E+00	4.216E-09	2.0010E+00	3.737E-08
2.1010E+00	8.340E-09	2.1010E+00	1.360E-08
2.2010E+00	1.070E-08	2.2010E+00	-1.034E-08
2.3010E+00	1.106E-08	2.3010E+00	-3.427E-08
2.4010E+00	8.829E-09	2.4010E+00	-2.751E-08
2.5010E+00	5.720E-09	2.5010E+00	-2.044E-08
2.6010E+00	3.328E-09	2.6010E+00	-1.337E-08
2.7010E+00	1.637E-09	2.7010E+00	-1.747E-08
2.8010E+00	9.762E-11	2.8010E+00	-2.171E-08
2.9010E+00	-1.860E-09	2.9010E+00	-2.594E-08
3.0010E+00	-4.243E-09	3.0010E+00	-1.587E-08
3.1010E+00	-6.341E-09	3.1010E+00	-5.705E-09
3.2010E+00	-7.421E-09	3.2010E+00	4.468E-09
3.3010E+00	-7.462E-09	3.3010E+00	7.080E-09
3.4010E+00	-6.700E-09	3.4010E+00	9.595E-09
3.5010E+00	-6.066E-09	3.5010E+00	1.211E-08
3.6010E+00	-4.981E-09	3.6010E+00	8.568E-09
3.7010E+00	-3.944E-09	3.7010E+00	4.965E-09
3.8010E+00	-3.267E-09	3.8010E+00	1.362E-09
3.9010E+00	-2.751E-09	3.9010E+00	7.547E-09
4.0010E+00	-2.511E-09	4.0010E+00	1.383E-08
4.1010E+00	-1.442E-09	4.1010E+00	2.011E-08
4.2010E+00	2.552E-10	4.2010E+00	7.090E-09
4.3010E+00	1.620E-09	4.3010E+00	-6.123E-09
4.4010E+00	1.673E-09	4.4010E+00	-1.934E-08
4.5010E+00	4.602E-10	4.5010E+00	-6.782E-09
4.6010E+00	-9.186E-10	4.6010E+00	6.032E-09
4.7010E+00	-9.561E-10	4.7010E+00	1.880E-08
4.8010E+00	2.878E-10	4.8010E+00	4.807E-09
4.9010E+00	1.486E-09	4.9010E+00	-9.403E-09
5.0010E+00	1.259E-09	5.0010E+00	-2.366E-08
5.1010E+00	-3.941E-10	5.1010E+00	-1.016E-08
5.2010E+00	-2.097E-09	5.2010E+00	3.620E-09
5.3010E+00	-2.426E-09	5.3010E+00	1.740E-08
5.4010E+00	-1.375E-09	5.4010E+00	7.744E-09
5.5010E+00	-1.057E-10	5.5010E+00	-2.154E-09
5.6010E+00	1.737E-10	5.6010E+00	-1.205E-08
5.7010E+00	-5.366E-10	5.7010E+00	-5.995E-09
5.8010E+00	-1.447E-09	5.8010E+00	2.237E-10
5.9010E+00	-1.735E-09	5.9010E+00	6.446E-09
6.0010E+00	-1.402E-09	6.0010E+00	5.734E-09
6.1010E+00	-7.895E-10	6.1010E+00	4.952E-09
6.2010E+00	-2.552E-10	6.2010E+00	4.167E-09
6.3010E+00	2.008E-10	6.3010E+00	-1.089E-09
6.4010E+00	3.570E-10	6.4010E+00	-6.391E-09
6.5010E+00	-1.700E-11	6.5010E+00	-1.167E-08
6.6010E+00	-9.213E-10	6.6010E+00	-1.408E-09
6.7010E+00	-1.584E-09	6.7010E+00	9.037E-09
6.8010E+00	-1.203E-09	6.8010E+00	1.949E-08
6.9010E+00	2.236E-10	6.9010E+00	4.613E-09
7.0010E+00	1.441E-09	7.0010E+00	-1.051E-08
7.1010E+00	1.146E-09	7.1010E+00	-2.564E-08
7.2010E+00	-6.616E-10	7.2010E+00	-7.982E-09
7.3010E+00	-2.359E-09	7.3010E+00	1.001E-08
7.4010E+00	-2.258E-09	7.4010E+00	2.800E-08
7.5010E+00	-3.570E-10	7.5010E+00	9.703E-09
7.6010E+00	1.547E-09	7.6010E+00	-8.764E-09
7.7010E+00	1.583E-09	7.7010E+00	-2.763E-08
7.8010E+00	-2.462E-10	7.8010E+00	-1.077E-08
7.9010E+00	-2.184E-09	7.9010E+00	6.401E-09
8.0010E+00	-2.400E-09	8.0010E+00	2.367E-08
8.1010E+00	-8.937E-10	8.1010E+00	1.060E-08
8.2010E+00	8.353E-10	8.2010E+00	-2.773E-09
8.3010E+00	1.227E-09	8.3010E+00	-1.615E-08
8.4010E+00	2.808E-10	8.4010E+00	-6.728E-09
8.5010E+00	-7.753E-10	8.5010E+00	-1.077E-09
8.6010E+00	-1.465E-09	8.6010E+00	6.533E-09
8.7010E+00	-1.193E-09	8.7010E+00	5.994E-09
8.8010E+00	-5.625E-10	8.8010E+00	5.373E-09
8.9010E+00	5.724E-12	8.9010E+00	4.751E-09
9.0010E+00	5.122E-10	9.0010E+00	-2.151E-09
9.1010E+00	6.453E-10	9.1010E+00	-9.115E-09
9.2010E+00	8.203E-11	9.2010E+00	-1.600E-08
9.3010E+00	-1.178E-09	9.3010E+00	-2.170E-09
9.4010E+00	-2.162E-09	9.4010E+00	1.170E-08
9.5010E+00	-1.617E-09	9.5010E+00	2.600E-08
9.6010E+00	7.782E-10		

$$K_r = 1.625 \times \text{Nominal}$$

$$T = 0.3 \text{ sec}$$

$$K_i = 0.5 \times \text{Nominal}$$

$$K_{WT} = 100$$

$$K_p = 1.25 \times \text{Nominal}$$

$$H_{WT} = 1$$

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Figure 6-40.

TIME	10011	10001
0.	1.000E-07	0.
1.0100E-01	7.453E-08	-8.000E-08
2.0100E-01	8.231E-08	-1.700E-07
3.0100E-01	6.032E-08	-2.637E-07
4.0100E-01	3.582E-08	-2.171E-07
5.0100E-01	1.400E-08	-1.734E-07
6.0100E-01	-3.001E-07	-1.076E-07
7.0100E-01	-1.704E-08	-1.200E-07
8.0100E-01	-2.747E-08	-8.074E-08
9.0100E-01	-3.437E-08	-5.131E-08
1.0010E+00	-3.808E-08	-3.266E-08
1.1010E+00	-4.072E-08	-1.417E-08
1.2010E+00	-4.142E-08	4.300E-07
1.3010E+00	-4.000E-08	2.317E-06
1.4010E+00	-3.678E-08	4.207E-06
1.5010E+00	-3.163E-08	6.070E-06
1.6010E+00	-2.641E-08	4.311E-06
1.7010E+00	-2.301E-08	2.470E-06
1.8010E+00	-2.143E-08	6.687E-07
1.9010E+00	-1.777E-08	2.287E-06
2.0010E+00	-1.680E-08	3.743E-06
2.1010E+00	-1.208E-08	5.077E-06
2.2010E+00	-7.712E-07	3.100E-06
2.3010E+00	-5.883E-07	5.600E-07
2.4010E+00	-6.073E-07	-1.781E-08
2.5010E+00	-7.735E-07	-2.611E-07
2.6010E+00	-7.114E-07	1.003E-08
2.7010E+00	-4.727E-07	3.267E-08
2.8010E+00	-2.219E-07	1.720E-08
2.9010E+00	-1.287E-07	1.377E-07
3.0010E+00	-1.740E-07	-1.441E-08
3.1010E+00	-3.071E-07	-8.001E-07
3.2010E+00	-3.040E-07	-1.372E-07
3.3010E+00	-3.340E-07	5.262E-07
3.4010E+00	-2.687E-07	7.827E-07
3.5010E+00	-1.780E-07	1.030E-08
3.6010E+00	-6.182E-10	1.288E-08
3.7010E+00	3.670E-11	7.320E-11
3.8010E+00	-6.036E-10	-1.288E-08
3.9010E+00	-2.040E-07	-2.064E-06
4.0010E+00	-4.044E-07	-3.878E-07
4.1010E+00	-3.310E-07	1.840E-08
4.2010E+00	-3.041E-10	4.077E-08
4.3010E+00	2.272E-07	1.164E-06
4.4010E+00	1.973E-07	-1.802E-06
4.5010E+00	-1.312E-07	-4.767E-06
4.6010E+00	-4.484E-07	-1.016E-06
4.7010E+00	-4.342E-07	1.777E-06
4.8010E+00	-8.807E-10	5.114E-06
4.9010E+00	2.673E-07	1.737E-06
5.0010E+00	2.772E-07	-1.301E-06
5.1010E+00	7.103E-11	-4.041E-06
5.2010E+00	-3.177E-07	1.740E-06
5.3010E+00	-3.808E-07	7.208E-07
5.4010E+00	-1.707E-07	3.301E-06
5.5010E+00	8.403E-10	1.781E-06
5.6010E+00	1.804E-07	1.368E-07
5.7010E+00	1.117E-07	-1.007E-06
5.8010E+00	-2.736E-10	-1.207E-06
5.9010E+00	-1.400E-07	-7.730E-07
6.0010E+00	-2.260E-07	-7.266E-07
6.1010E+00	-2.301E-07	5.034E-07
6.2010E+00	-1.103E-07	1.844E-06
6.3010E+00	1.338E-09	3.134E-06
6.4010E+00	3.077E-07	3.466E-07
6.5010E+00	2.030E-07	-2.461E-06
6.6010E+00	-1.860E-07	-5.310E-06
6.7010E+00	-5.188E-07	-1.267E-06
6.8010E+00	-4.377E-07	2.840E-06
6.9010E+00	5.024E-10	6.908E-06
7.0010E+00	5.084E-07	2.116E-06
7.1010E+00	4.730E-07	-2.810E-06
7.2010E+00	-5.402E-10	-7.746E-06
7.3010E+00	-5.830E-07	-2.734E-06
7.4010E+00	-6.013E-07	2.378E-06
7.5010E+00	-1.077E-07	7.471E-06
7.6010E+00	4.227E-07	3.020E-06
7.7010E+00	4.770E-07	-1.038E-06
7.8010E+00	1.101E-07	-6.101E-06
7.9010E+00	-3.366E-07	-2.876E-06
8.0010E+00	-4.640E-07	3.877E-07
8.1010E+00	-2.610E-07	3.672E-06
8.2010E+00	4.100E-10	2.333E-06
8.3010E+00	2.000E-07	7.462E-07
8.4010E+00	2.308E-07	-4.402E-07
8.5010E+00	1.404E-07	-1.363E-06
8.6010E+00	-4.172E-10	-2.280E-06
8.7010E+00	-3.106E-07	-3.178E-06
8.8010E+00	-4.731E-07	7.176E-10
8.9010E+00	-2.972E-07	3.420E-06
9.0010E+00	2.117E-07	6.708E-06
9.1010E+00	6.207E-07	1.327E-06
9.2010E+00	4.777E-07	-4.186E-06
9.3010E+00	-2.167E-07	-7.700E-06
9.4010E+00	-8.437E-07	-2.708E-06
9.5010E+00	-7.083E-07	4.417E-06
9.6010E+00	3.907E-10	1.104E-07

$$K_r = 1.95 \times \text{Nominal}$$

$$K_i = 0.5 \times \text{Nominal}$$

$$K_p = 1.25 \times \text{Nominal}$$

$$T = 0.3 \text{ sec}$$

$$K_{WT} = 100$$

$$H_{WT} = 1$$

Figure 6-41.

Time	THU 1	THU 1	THU 1
0.	1.000E-07	1.000E-07	1.000E-07
1.010E-01	7.500E-08	7.500E-08	7.500E-08
2.010E-01	6.731E-08	6.731E-08	6.731E-08
3.010E-01	6.032E-08	6.032E-08	6.032E-08
4.010E-01	5.270E-08	5.270E-08	5.270E-08
5.010E-01	4.337E-08	4.337E-08	4.337E-08
6.010E-01	3.266E-08	3.266E-08	3.266E-08
7.010E-01	2.054E-08	2.054E-08	2.054E-08
8.010E-01	1.007E-08	1.007E-08	1.007E-08
9.010E-01	0.070E-08	0.070E-08	0.070E-08
1.0010E+00	-6.154E-08	-6.154E-08	-6.154E-08
1.1010E+00	-6.084E-08	-6.084E-08	-6.084E-08
1.2010E+00	-5.752E-08	-5.752E-08	-5.752E-08
1.3010E+00	-5.159E-08	-5.159E-08	-5.159E-08
1.4010E+00	-4.356E-08	-4.356E-08	-4.356E-08
1.5010E+00	-3.377E-08	-3.377E-08	-3.377E-08
1.6010E+00	-2.283E-08	-2.283E-08	-2.283E-08
1.7010E+00	-1.136E-08	-1.136E-08	-1.136E-08
1.8010E+00	-2.555E-09	-2.555E-09	-2.555E-09
1.9010E+00	3.444E-09	3.444E-09	3.444E-09
2.0010E+00	6.820E-09	6.820E-09	6.820E-09
2.1010E+00	8.712E-09	8.712E-09	8.712E-09
2.2010E+00	7.317E-09	7.317E-09	7.317E-09
2.3010E+00	8.672E-09	8.672E-09	8.672E-09
2.4010E+00	7.578E-09	7.578E-09	7.578E-09
2.5010E+00	6.360E-09	6.360E-09	6.360E-09
2.6010E+00	5.018E-09	5.018E-09	5.018E-09
2.7010E+00	3.146E-09	3.146E-09	3.146E-09
2.8010E+00	3.219E-10	3.219E-10	3.219E-10
2.9010E+00	-3.455E-09	-3.455E-09	-3.455E-09
3.0010E+00	-7.302E-09	-7.302E-09	-7.302E-09
3.1010E+00	-9.057E-09	-9.057E-09	-9.057E-09
3.2010E+00	-8.624E-09	-8.624E-09	-8.624E-09
3.3010E+00	-8.383E-09	-8.383E-09	-8.383E-09
3.4010E+00	-4.720E-09	-4.720E-09	-4.720E-09
3.5010E+00	-4.050E-09	-4.050E-09	-4.050E-09
3.6010E+00	-4.326E-09	-4.326E-09	-4.326E-09
3.7010E+00	-4.545E-09	-4.545E-09	-4.545E-09
3.8010E+00	-4.294E-09	-4.294E-09	-4.294E-09
3.9010E+00	-3.573E-09	-3.573E-09	-3.573E-09
4.0010E+00	-2.408E-09	-2.408E-09	-2.408E-09
4.1010E+00	-8.279E-10	-8.279E-10	-8.279E-10
4.2010E+00	1.166E-09	1.166E-09	1.166E-09
4.3010E+00	2.774E-09	2.774E-09	2.774E-09
4.4010E+00	3.108E-09	3.108E-09	3.108E-09
4.5010E+00	1.503E-09	1.503E-09	1.503E-09
4.6010E+00	-1.379E-09	-1.379E-09	-1.379E-09
4.7010E+00	-2.840E-09	-2.840E-09	-2.840E-09
4.8010E+00	-2.344E-09	-2.344E-09	-2.344E-09
4.9010E+00	-1.803E-11	-1.803E-11	-1.803E-11
5.0010E+00	1.719E-09	1.719E-09	1.719E-09
5.1010E+00	1.679E-09	1.679E-09	1.679E-09
5.2010E+00	4.622E-10	4.622E-10	4.622E-10
5.3010E+00	-1.433E-09	-1.433E-09	-1.433E-09
5.4010E+00	-2.661E-09	-2.661E-09	-2.661E-09
5.5010E+00	-3.224E-09	-3.224E-09	-3.224E-09
5.6010E+00	-3.082E-09	-3.082E-09	-3.082E-09
5.7010E+00	-2.142E-09	-2.142E-09	-2.142E-09
5.8010E+00	-3.988E-10	-3.988E-10	-3.988E-10
5.9010E+00	1.810E-09	1.810E-09	1.810E-09
6.0010E+00	2.433E-09	2.433E-09	2.433E-09
6.1010E+00	1.079E-09	1.079E-09	1.079E-09
6.2010E+00	-2.057E-09	-2.057E-09	-2.057E-09
6.3010E+00	-4.030E-09	-4.030E-09	-4.030E-09
6.4010E+00	-3.595E-09	-3.595E-09	-3.595E-09
6.5010E+00	-7.531E-10	-7.531E-10	-7.531E-10
6.6010E+00	2.321E-09	2.321E-09	2.321E-09
6.7010E+00	3.360E-09	3.360E-09	3.360E-09
6.8010E+00	2.367E-09	2.367E-09	2.367E-09
6.9010E+00	1.113E-10	1.113E-10	1.113E-10
7.0010E+00	-1.520E-09	-1.520E-09	-1.520E-09
7.1010E+00	-2.442E-09	-2.442E-09	-2.442E-09
7.2010E+00	-2.824E-09	-2.824E-09	-2.824E-09
7.3010E+00	-1.877E-09	-1.877E-09	-1.877E-09
7.4010E+00	-1.697E-10	-1.697E-10	-1.697E-10
7.5010E+00	2.394E-09	2.394E-09	2.394E-09
7.6010E+00	3.510E-09	3.510E-09	3.510E-09
7.7010E+00	2.236E-09	2.236E-09	2.236E-09
7.8010E+00	-1.427E-09	-1.427E-09	-1.427E-09
7.9010E+00	-4.826E-09	-4.826E-09	-4.826E-09
8.0010E+00	-5.200E-09	-5.200E-09	-5.200E-09
8.1010E+00	-2.548E-09	-2.548E-09	-2.548E-09
8.2010E+00	1.592E-09	1.592E-09	1.592E-09
8.3010E+00	3.455E-09	3.455E-09	3.455E-09
8.4010E+00	2.873E-09	2.873E-09	2.873E-09
8.5010E+00	2.439E-10	2.439E-10	2.439E-10
8.6010E+00	-1.930E-09	-1.930E-09	-1.930E-09
8.7010E+00	-3.214E-09	-3.214E-09	-3.214E-09
8.8010E+00	-3.600E-09	-3.600E-09	-3.600E-09
8.9010E+00	-2.876E-09	-2.876E-09	-2.876E-09
9.0010E+00	-7.554E-10	-7.554E-10	-7.554E-10
9.1010E+00	2.162E-09	2.162E-09	2.162E-09
9.2010E+00	4.430E-09	4.430E-09	4.430E-09
9.3010E+00	3.719E-09	3.719E-09	3.719E-09
9.4010E+00	2.820E-11	2.820E-11	2.820E-11
9.5010E+00	-4.765E-09	-4.765E-09	-4.765E-09
9.6010E+00	-6.074E-09	-6.074E-09	-6.074E-09
9.7010E+00			
9.8010E+00			
9.9010E+00			

$$K_r = 1.55 \times \text{Nominal}$$

$$K_i = 0.5 \times \text{Nominal}$$

$$K_p = 1.25 \times \text{Nominal}$$

$$T = 0.325 \text{ sec}$$

$$K_{WT} = 100$$

$$H_{WT} = 1$$

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OF POOR QUALITY

Figure 6-42.

Time	Time	Time
1.0010E-01	1.000E-07	1.000E-08
1.0100E-01	7.553E-08	8.040E-08
1.0200E-01	8.1231E-08	1.739E-07
1.0300E-01	6.035E-08	2.037E-07
1.0400E-01	3.107E-08	2.708E-07
1.0500E-01	3.837E-07	2.041E-07
1.0600E-01	1.770E-08	2.177E-07
1.0700E-01	3.770E-08	1.013E-07
1.0800E-01	0.460E-08	1.184E-07
1.0900E-01	-6.278E-08	0.122E-08
1.1000E+00	-6.480E-08	1.370E-08
1.1100E+00	-6.084E-08	0.205E-08
1.1200E+00	-5.505E-08	6.320E-08
1.1300E+00	-4.810E-08	7.397E-08
1.1400E+00	-4.025E-08	8.471E-08
1.1500E+00	-3.188E-08	8.676E-08
1.1600E+00	-2.286E-08	6.911E-08
1.1700E+00	-1.384E-08	9.126E-08
1.1800E+00	-4.835E-07	8.401E-08
1.1900E+00	2.713E-07	6.697E-08
1.2000E+00	8.558E-07	4.972E-08
1.2100E+00	1.270E-08	3.287E-08
1.2200E+00	1.460E-08	5.004E-07
1.2300E+00	1.570E-08	-2.295E-08
1.2400E+00	1.001E-08	-5.091E-08
1.2500E+00	4.076E-07	-5.611E-08
1.2600E+00	-6.124E-10	-3.785E-08
1.2700E+00	-3.454E-07	-1.919E-08
1.2800E+00	-4.401E-07	-7.324E-10
1.2900E+00	-4.448E-07	6.196E-10
1.3000E+00	-4.327E-07	1.803E-07
1.3100E+00	-4.087E-07	2.986E-07
1.3200E+00	-3.848E-07	-6.826E-10
1.3300E+00	-4.348E-07	-9.347E-07
1.3400E+00	-5.717E-07	-1.803E-08
1.3500E+00	-7.955E-07	-2.672E-08
1.3600E+00	-9.526E-07	-4.401E-09
1.3700E+00	-8.834E-07	1.824E-08
1.3800E+00	-5.877E-07	4.089E-08
1.3900E+00	-1.136E-09	4.396E-08
1.4000E+00	2.375E-07	2.665E-08
1.4100E+00	4.174E-07	7.333E-07
1.4200E+00	4.262E-07	-7.978E-07
1.4300E+00	3.110E-07	-1.476E-08
1.4400E+00	1.270E-07	-2.183E-08
1.4500E+00	-1.257E-07	-2.671E-08
1.4600E+00	-4.111E-07	-2.062E-08
1.4700E+00	-5.030E-07	2.437E-07
1.4800E+00	-3.622E-07	2.571E-08
1.4900E+00	1.119E-10	4.678E-08
1.5000E+00	3.827E-07	2.470E-08
1.5100E+00	5.091E-07	3.396E-10
1.5200E+00	3.898E-07	-2.421E-08
1.5300E+00	6.325E-10	-3.312E-08
1.5400E+00	-2.310E-07	-2.574E-08
1.5500E+00	-4.516E-07	-1.837E-08
1.5600E+00	-5.985E-07	-1.100E-08
1.5700E+00	-6.138E-07	8.055E-07
1.5800E+00	-4.374E-07	2.724E-08
1.5900E+00	-6.911E-10	4.641E-08
1.6000E+00	4.287E-07	4.021E-08
1.6100E+00	6.678E-07	7.573E-07
1.6200E+00	5.806E-07	-2.502E-08
1.6300E+00	1.674E-07	-5.762E-08
1.6400E+00	-3.086E-07	-3.705E-08
1.6500E+00	-5.736E-07	-1.595E-08
1.6600E+00	-6.276E-07	3.157E-07
1.6700E+00	-4.862E-07	1.982E-08
1.6800E+00	-2.483E-07	2.776E-08
1.6900E+00	6.903E-10	3.571E-08
1.7000E+00	4.658E-07	4.365E-08
1.7100E+00	7.358E-07	-2.418E-08
1.7200E+00	6.645E-07	-5.830E-08
1.7300E+00	2.521E-07	-5.811E-08
1.7400E+00	-4.174E-07	-2.223E-08
1.7500E+00	-8.191E-07	1.367E-08
1.7600E+00	-8.617E-07	4.757E-08
1.7700E+00	-5.457E-07	4.106E-08
1.7800E+00	-9.035E-10	3.209E-08
1.7900E+00	2.754E-07	2.312E-08
1.8000E+00	5.514E-07	4.837E-07
1.8100E+00	5.514E-07	-2.311E-08
1.8200E+00	7.147E-07	-5.105E-08
1.8300E+00	6.235E-07	-7.901E-08
1.8400E+00	2.527E-07	-3.323E-08
1.8500E+00	-3.976E-07	1.330E-08
1.8600E+00	-9.624E-07	5.984E-08
1.8700E+00	-1.062E-08	6.886E-08
1.8800E+00	-6.964E-07	3.870E-08
1.8900E+00	4.277E-10	8.715E-07
1.9000E+00	5.817E-07	-2.106E-08
1.9100E+00	6.208E-07	-3.364E-08
1.9200E+00	7.690E-07	-4.604E-08
1.9300E+00	4.857E-07	-5.845E-08
1.9400E+00	8.729E-10	-4.054E-08
1.9500E+00	-4.352E-07	8.937E-07
1.9600E+00	-1.007E-08	
1.9700E+00	-1.166E-08	

$$K_r = 1.55 \times \text{Nominal}$$

$$K_i = 0.5 \times \text{Nominal}$$

$$K_p = 1.25 \times \text{Nominal}$$

$$T = 0.35 \text{ sec}$$

$$K_{WT} = 100$$

$$H_{WT} = 1$$

Figure 6-43.

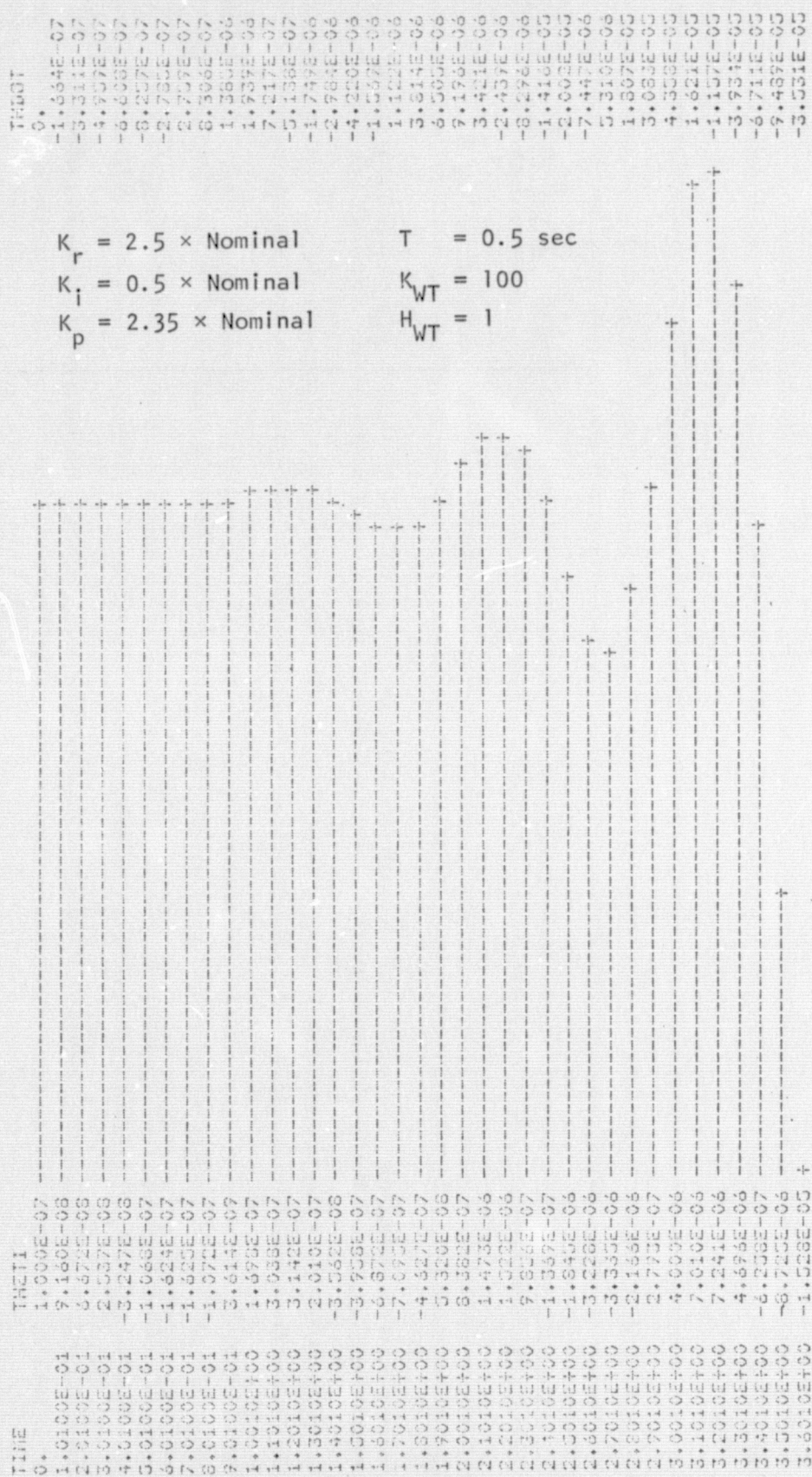


Figure 6-44.